Production cross section measurements and New isotope searches by BigRIPS separator at RIBF

--- Radioactive Isotopes produced from the ^{124}Xe , ^{70}Zn , ^{48}Ca, ^{18}O, and ^{238}U beams ---

Hiroshi Suzuki, N. Fukuda, D. Kameda, Y. Shimizu, H. Takeda, H. Sato, T. Ohnishi, N. Inabe, and T. Kubo

BigRIPS team, RNC, RIKEN

RIBF Seminar, RIKEN, Jan. 28, 2014

Outline

0. Introduction
    - RI beams at the BigRIPS separator
    - Production mechanism of RI beams
    - Particle Identification (PID) at BigRIPS

1. Production cross sections of radioactive isotopes (RIs) produced by projectile fragmentation
    - Neutron-deficient nuclei by projectile fragmentation from ^{124}Xe beams
        - Momentum distribution
    - Neutron-rich nuclei by projectile fragmentation from ^{70}Zn beams
    - Neutron-rich nuclei by projectile fragmentation from ^{48}Ca beams
    - Neutron-rich nuclei by projectile fragmentation from ^{18}O beams

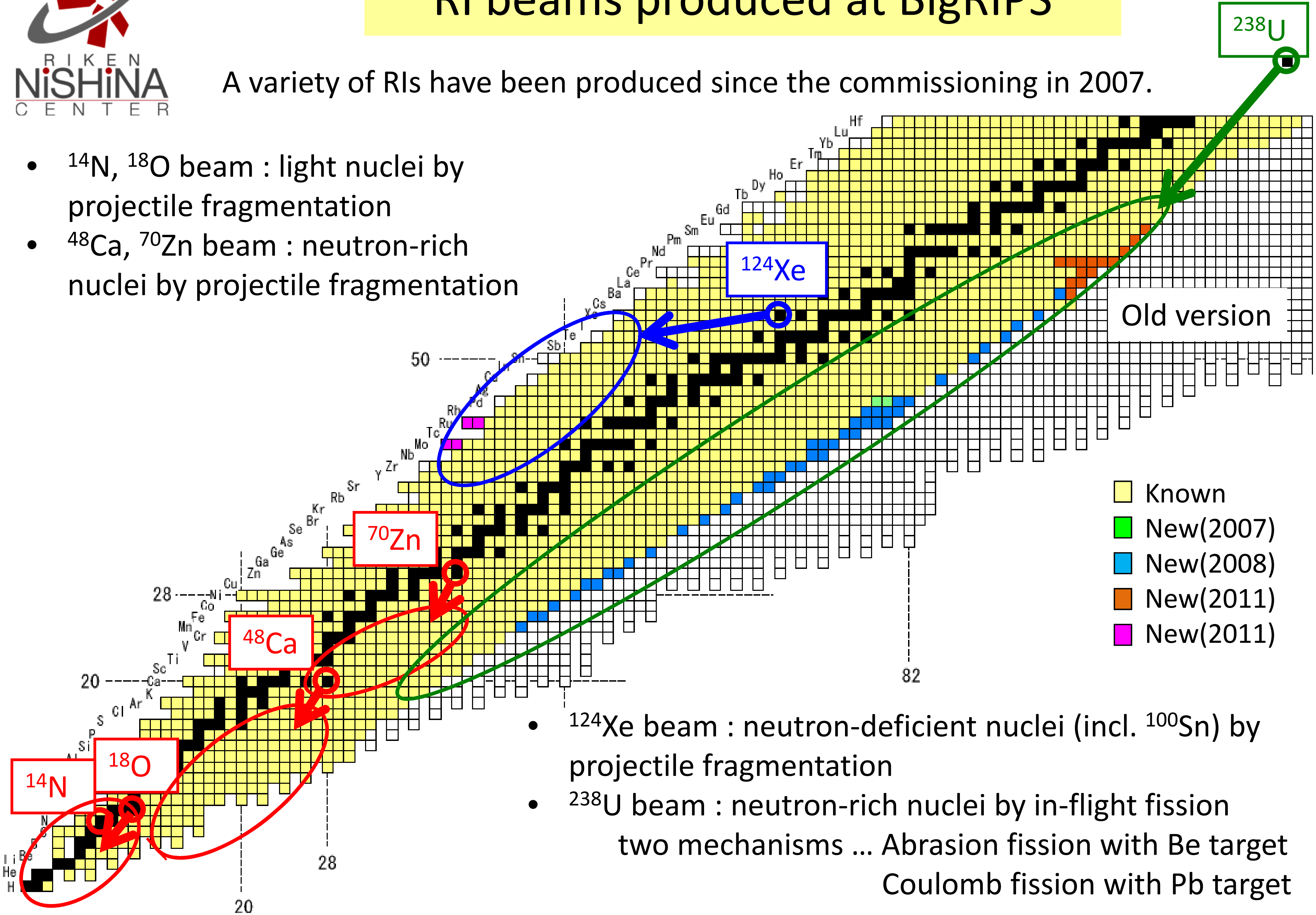
2. New isotopes in the ^{124}Xe beam experiment

3. Production rates (yields) of RIs produced by in-flight fission of ^{238}U beam
    - Abrasion fission case (using Be target)
    - Coulomb fission case (using Pb / W target)

RI beams produced at BigRIPS

A variety of RIs have been produced since the commissioning in 2007.

- ^{14}N, ^{18}O beam : light nuclei by projectile fragmentation
- ^{48}Ca, ^{70}Zn beam : neutron-rich nuclei by projectile fragmentation

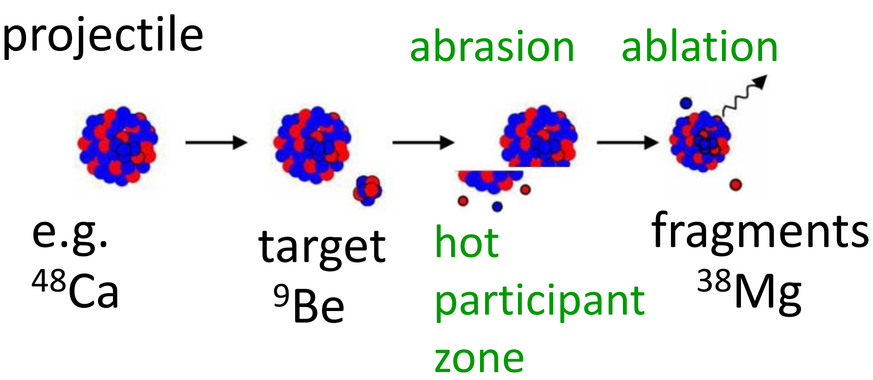


- ^{124}Xe beam : neutron-deficient nuclei (incl. ^{100}Sn) by projectile fragmentation
- ^{238}U beam : neutron-rich nuclei by in-flight fission
  two mechanisms … Abrasion fission with Be target
  Coulomb fission with Pb target

Production reactions of RI beams at BigRIPS

Projectile fragmentation

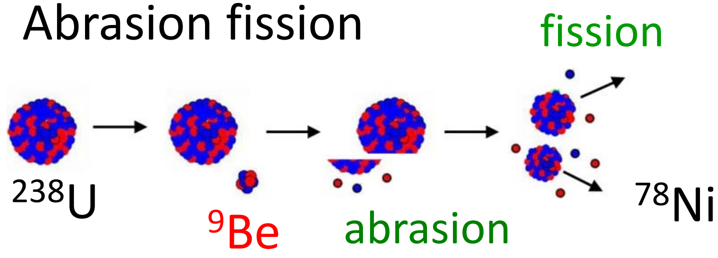
- Abrasion-ablation model



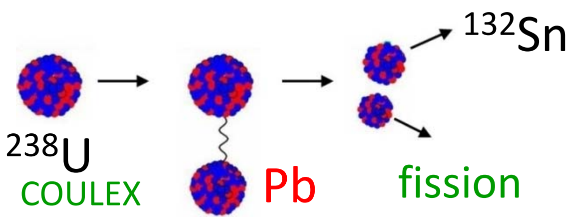
- All kinds of fragments (RI beams) lighter than projectile can be produced.

In-flight fission (of ^{238}U)

- Abrasion fission



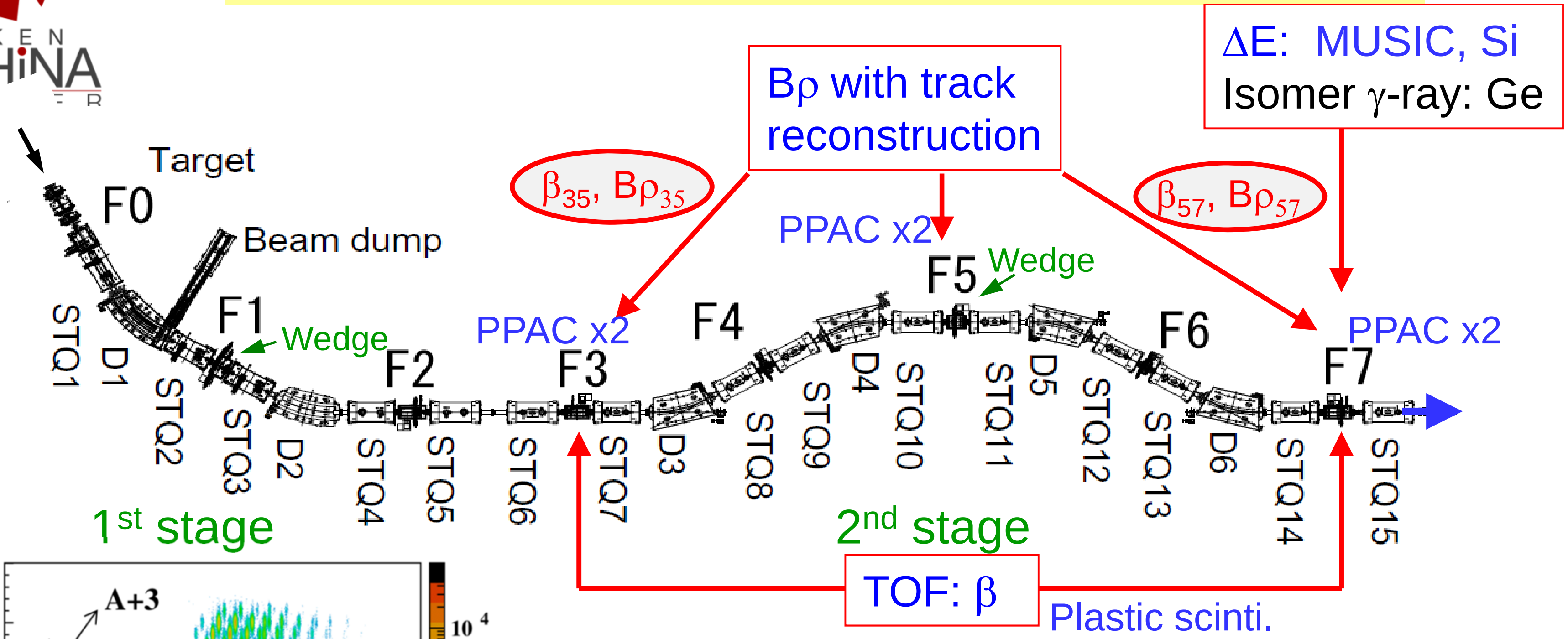
- Coulomb fission

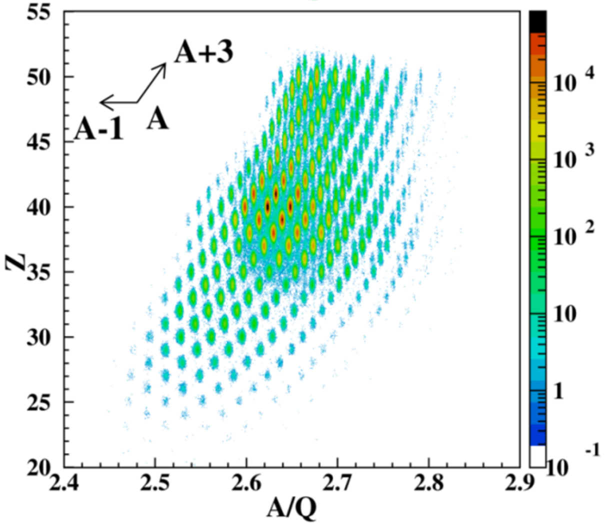


- Very powerful for medium heavy neutron-rich isotopes.

These figures are based on GSI figures.

Particle Identification scheme at BigRIPS





TOF-$B\rho$-ΔE method with track reconstruction @ 2nd stage

← *Z* vs *A/Q* plot

BigRIPS: T. Kubo, NIM B 204 (2003) 97 & T. Kubo *et al.* , IEEE Trans. Appl. Supercond. 17 (2007) 1069.

PID scheme: N. Fukuda *et al.*, NIM B 317 (2013) 323

Section 1

Production cross section of RIs produced by the projectile fragmentation

RIKEN NiSHiNA CENTER

Measurements with ^{124}Xe beam
Neutron-deficient isotopes by projectile fragmentation

- Cross section
- Momentum distribution

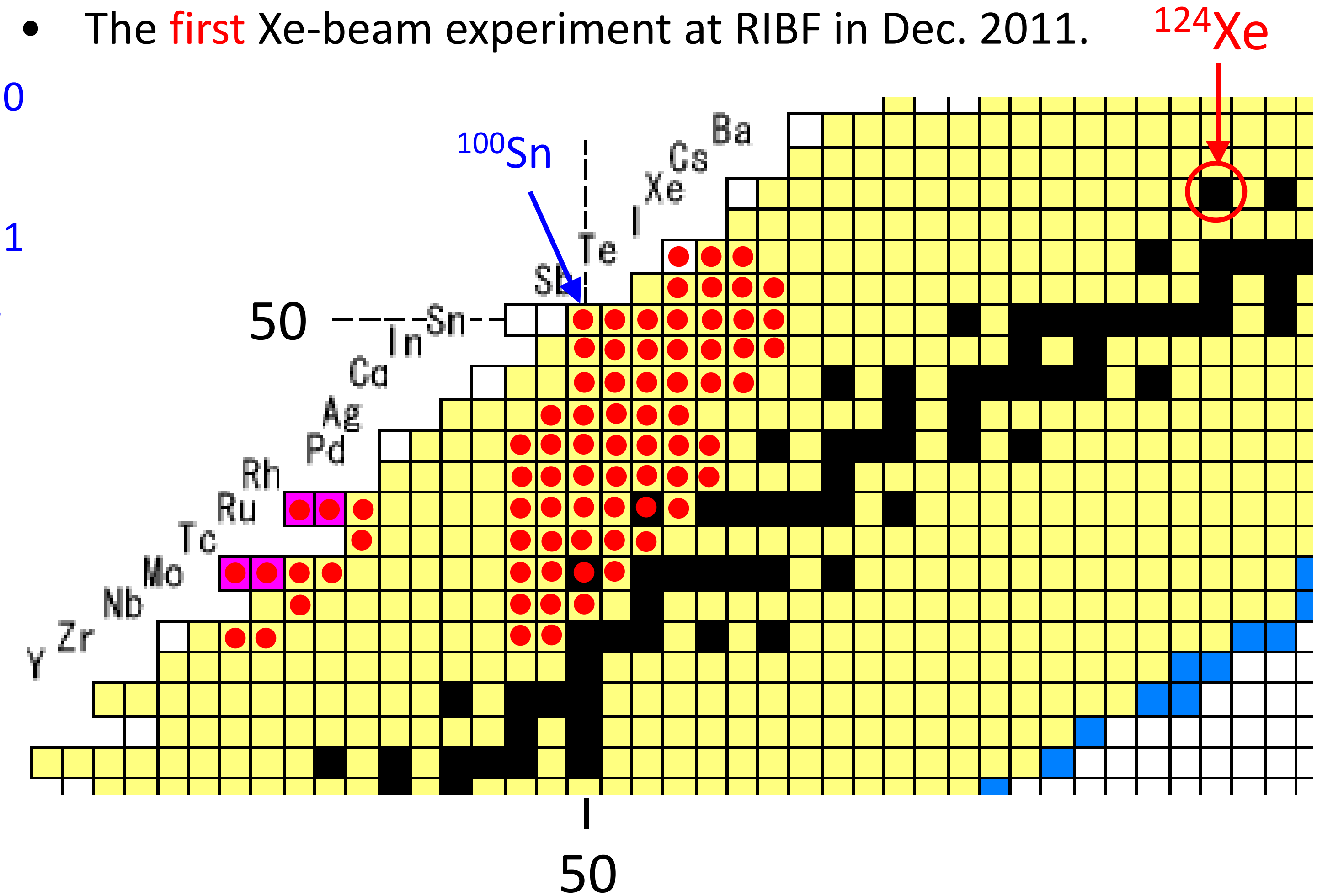
H. Suzuki, *et al*., NIMB 317, 756-768 (2013)

Yields of neutron-deficient RI beams using a ^{124}Xe beam at 345 MeV/u

- The first Xe-beam experiment at RIBF in Dec. 2011.

Yields [pps/pnA]

^{105}Te	0.00030
^{104}Sb	0.066
^{100}Sn	0.00011
^{101}Sn	0.0078
^{102}Sn	0.51
^{99}In	0.040
^{100}In	1.4
^{98}Cd	4.8
^{96}Ag	17
^{94}Pd	9.4
^{94}Rh	12000
^{92}Ru	7700



Recent ^{124}Xe-beam Intensity : ~35 pnA (Jun 2013)

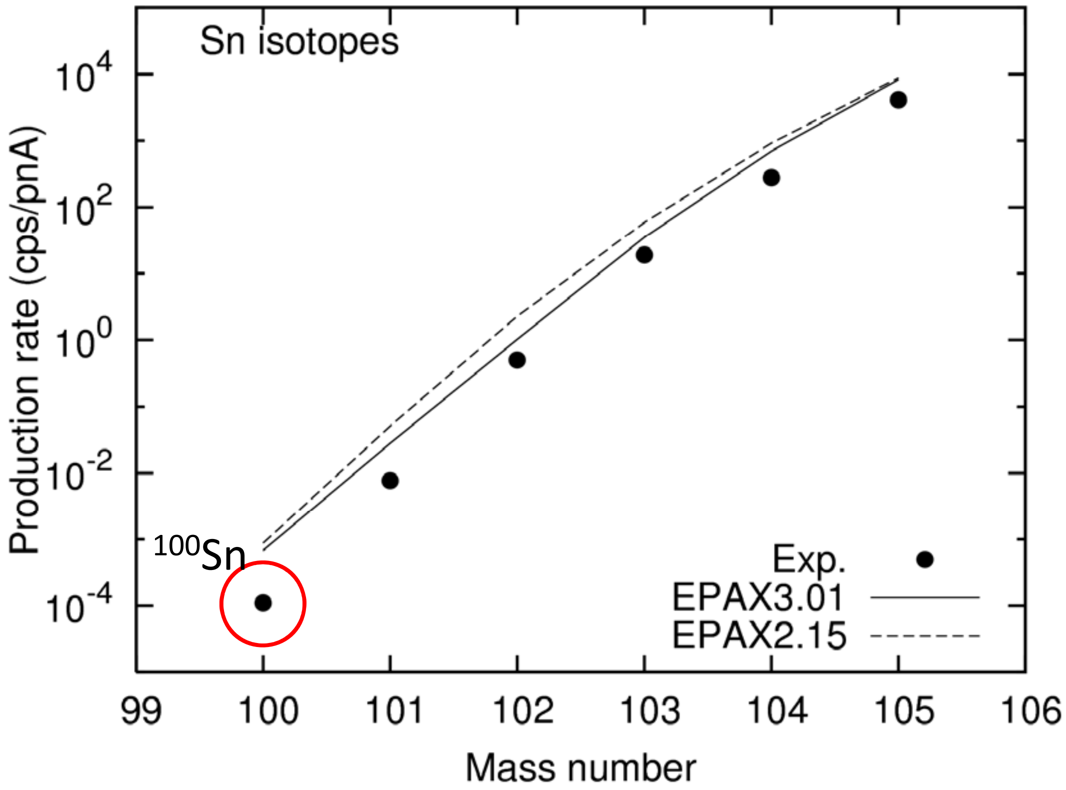
Production rate of neutron-deficient Sn isotopes from a ^{124}Xe beam at 345 MeV/u

RIKEN NISHINA CENTER

^{124}Xe 345 MeV/u + Be 4 mm $\Delta p/p$ = +/-2%

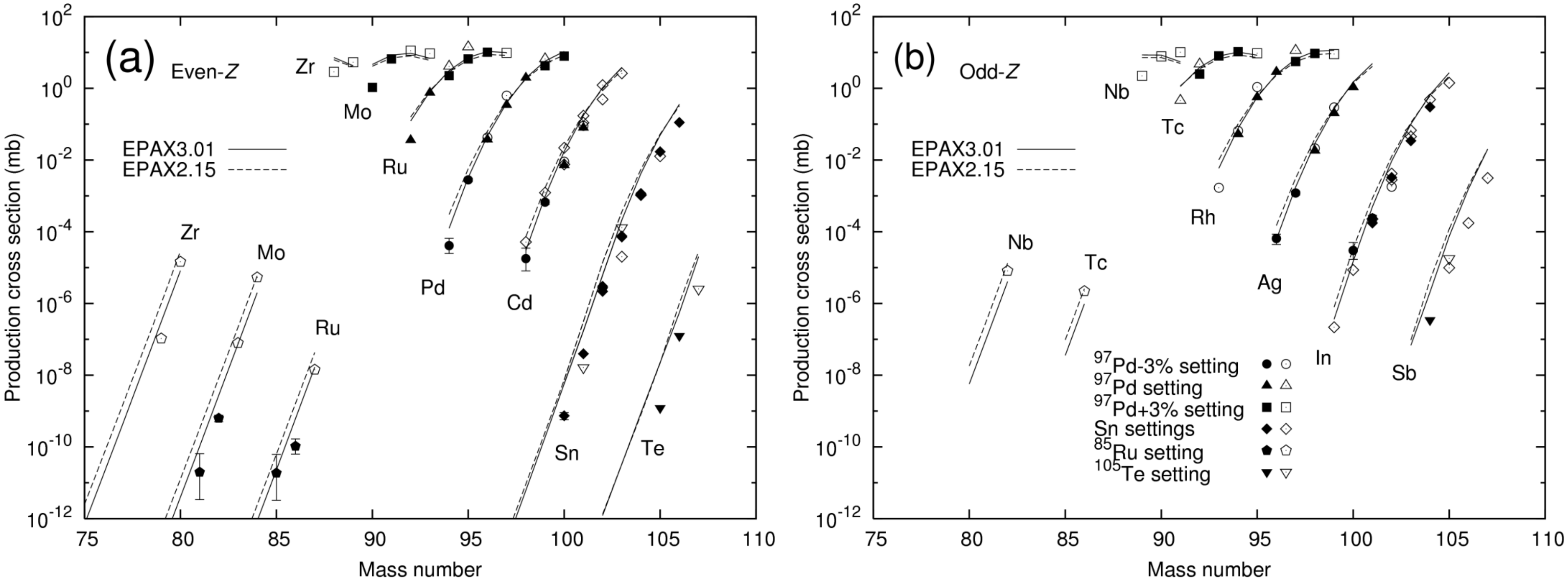
Yields [pps/pnA]

^{100}Sn	0.00011
^{101}Sn	0.0078
^{102}Sn	0.51
^{103}Sn	19
^{104}Sn	280
^{105}Sn	4200



- Production rate of ^{100}Sn is ~ 1/7 of EPAX 3.01.

Measured production cross sections comparison with EPAX 2.15 & 3.01 (^{124}Xe 345 MeV/u + Be)



Filled symbol: distribution peak is located inside the slit opening at each focus.
Open symbol: distribution peak is located outside at some foci.

- Fairly good agreement between the experimental results and EPAX 3.01.
- In more neutron-deficient region and higher *Z* region, the experimental cross sections are smaller than EPAX 3.01 (in the case of ^{100}Sn: 1/7).

Cross section of ^{100}Sn
Discrepancy between RIKEN and GSI

- There is a discrepancy between the cross section of ^{100}Sn measured at RIKEN and GSI (1 : 8).

	Facility	event	Cross section	Energy	Be target	
R0	RIKEN	23	0.74±0.17 pb*	345 MeV/u	4 mm	
R1	RIKEN	6	0.40±0.17 pb*	345 MeV/u	4 mm	preliminary
R2	RIKEN	12	0.71±0.21 pb*	345 MeV/u	4 mm	preliminary
R3	RIKEN	9	1.6±0.5 pb*	345 MeV/u	8 mm + W-0.2mm	preliminary
G0	GSI	259	5.8±2.1 pb	1000 MeV/u	32 mm (6 g/cm^2)	
G1	GSI	7	5 pb	1095 MeV/u	32 mm (6 g/cm^2)	

5.76 pb (EPAX3.01)
7.43 pb (EPAX2.15)

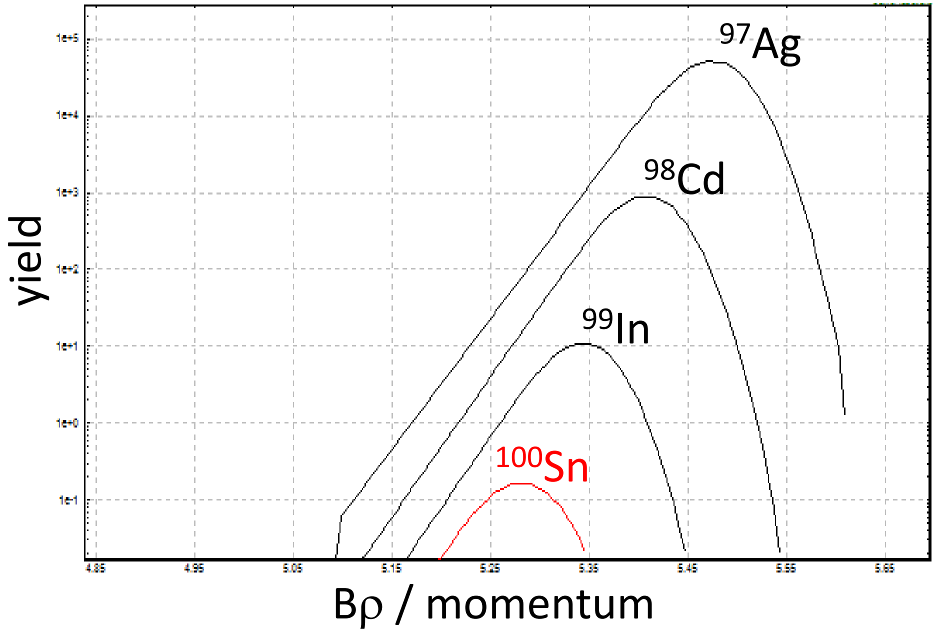
* : Only the statistical error is described.
The systematic one is assumed to be ~ 50%.

R0 : H.Suzuki, *et al*, NIMB 317, 756-768 (2013)
R1-R3: preliminary
R3: charge striping method
G0 : C.B.Hinke, *et al*, Nature (London) 486, 341 (2012)
G1 : R. Schneider, *et al*, Z. Phys. A 348, 241 (1994)

Is this discrepancy caused by…

- Energy dependence of the projectile?
- Secondary-reaction effect in the production target?
    - RIKEN (345 MeV/u, 4 mm): ~1.16, GSI (1 GeV/u, 32 mm): ~3 (by LISE++)

Momentum distribution



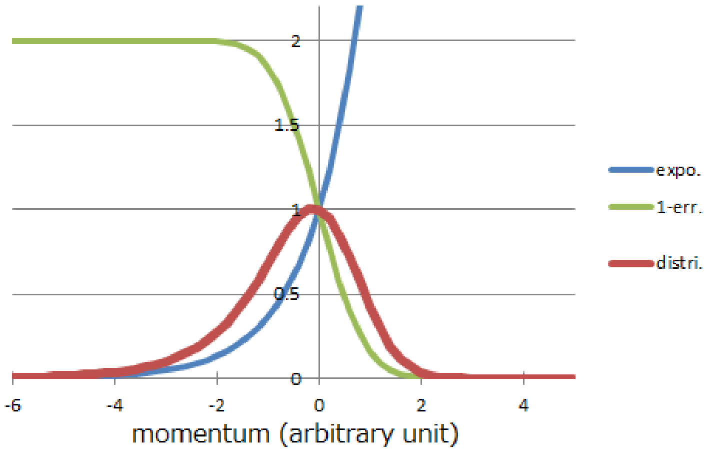
: The objective nuclei (cf: ^{100}Sn)

: The contaminant nuclei (cf: ^{99}In, ^{98}Cd, ^{97}Ag)

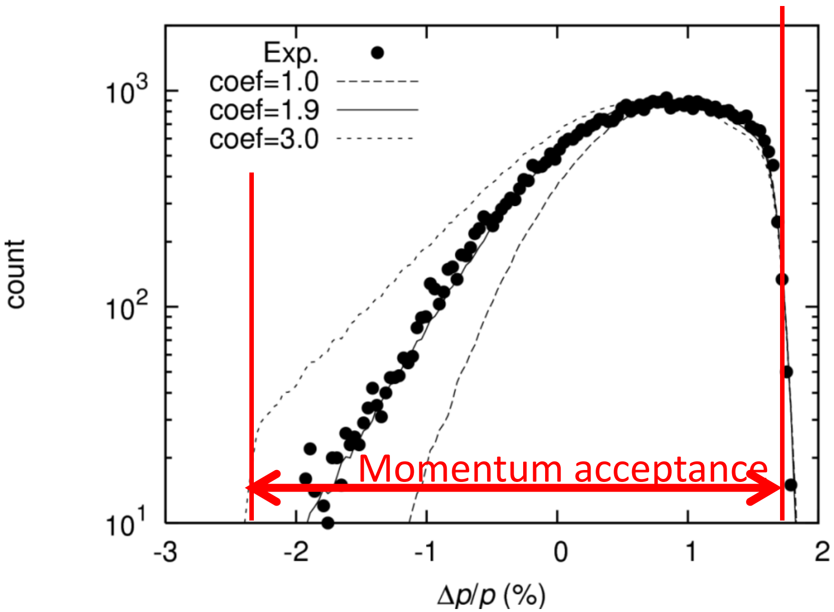
The low momentum tails of the contaminant nuclei make the purity worse.

- The low-momentum tails of the neutron deficient nuclei were measured.
- The shape of the low-momentum tail is very important especially for the neutron-deficient nuclei experiment.
- We searched a tail-parameter, named “coef” in the LISE^{++} calculation.

Low momentum tail

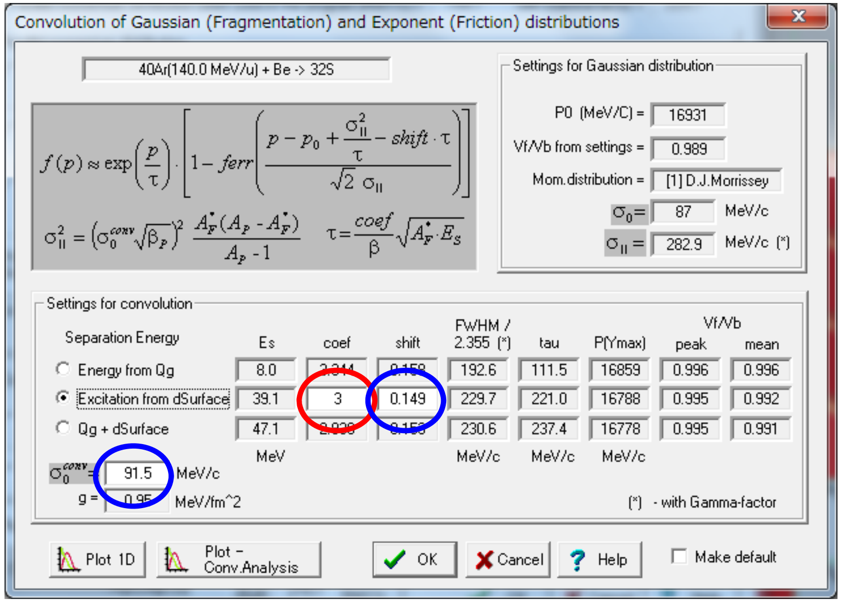


Concept of mom. distri. In LISE++
distri. = expo. x (1-err.)



Momentum distribution of ^{99}Rh
(Monte Carlo simulation)

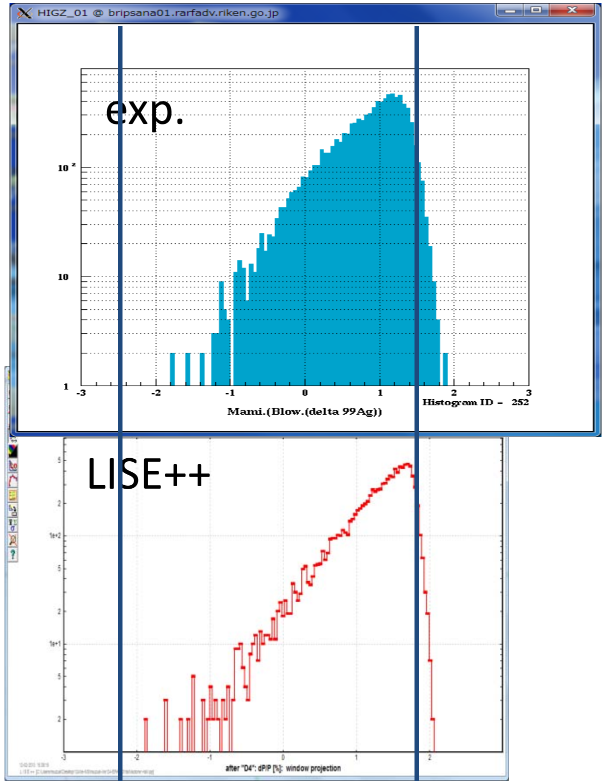
Production Mechanism
→ Settings (Projectile Fragmentation)
→ Momentum distribution
→ Settings



The “coef” value of 1.9 gives the best result.

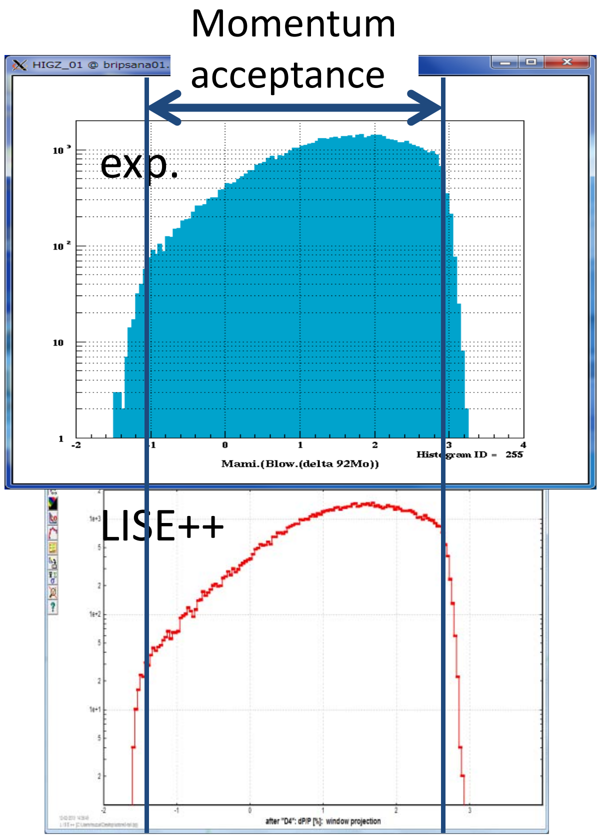
Cf) “coef” =
5.758 : 26-2200 MeV/u (mainly <100 MeV/u)
O. Tarasov, Nuclear Physics A734 (2004) 536-540
3 : 140-MeV/u NSCL data
O. Tarasov, private communication
1.9 : 345-MeV/u ^{124}Xe-beam data

$B\rho$ distribution of other nuclei



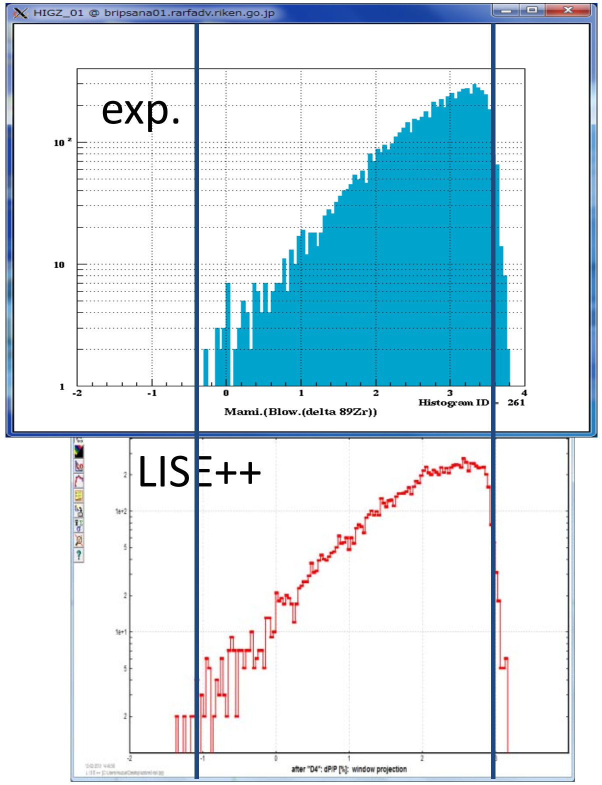
^{99}Ag (Z=47)

(isotone1 setting)



^{92}Mo (Z=42)

(isotone3 setting)

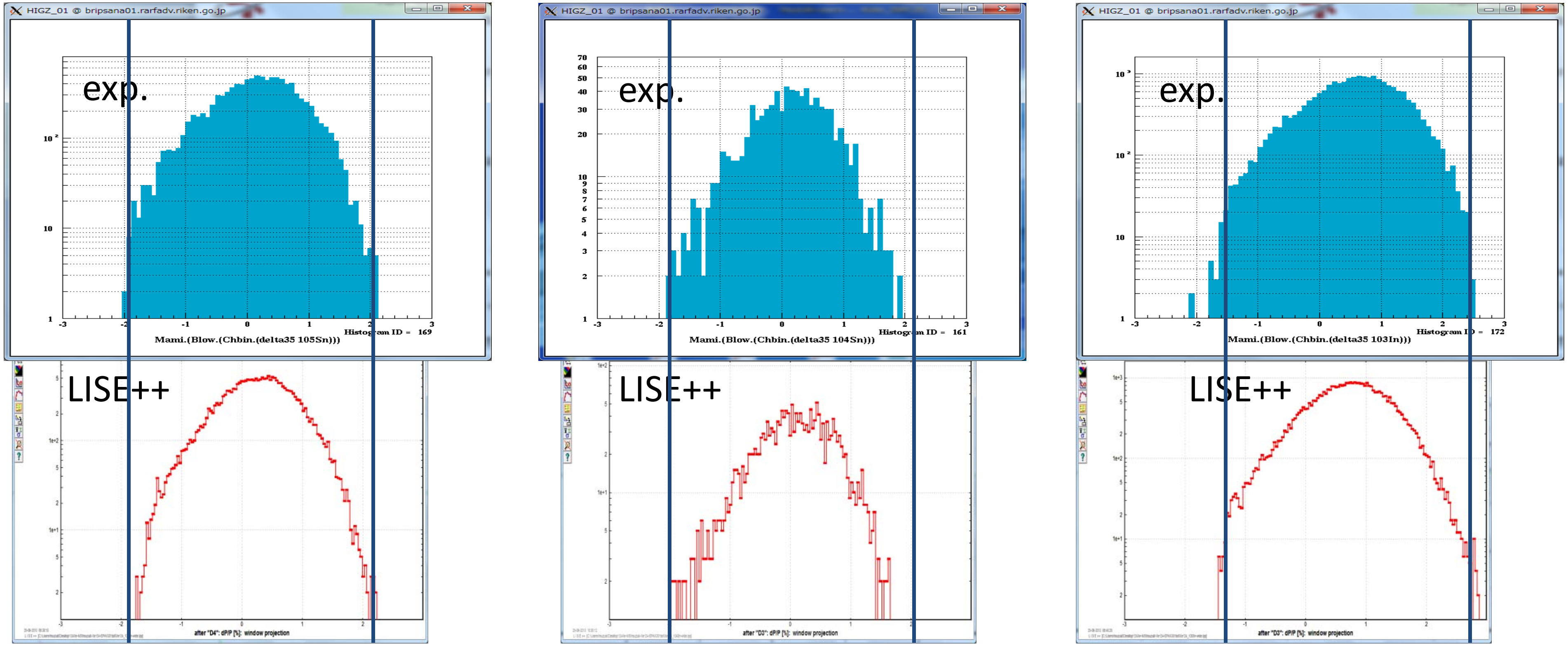


^{89}Zr (Z=40)

(isotone3 setting)

^{124}Xe beam + Be @ 345 MeV/u, "coef" = 1.9

$B\rho$ distribution of other nuclei



^{105}Sn (Z=50)

(105Sn setting)

^{104}Sn (Z=50)

(104Sn setting)

^{103}In (Z=49)

(105Sn setting)

^{124}Xe beam + Be @ 345 MeV/u, “coef” = 1.9

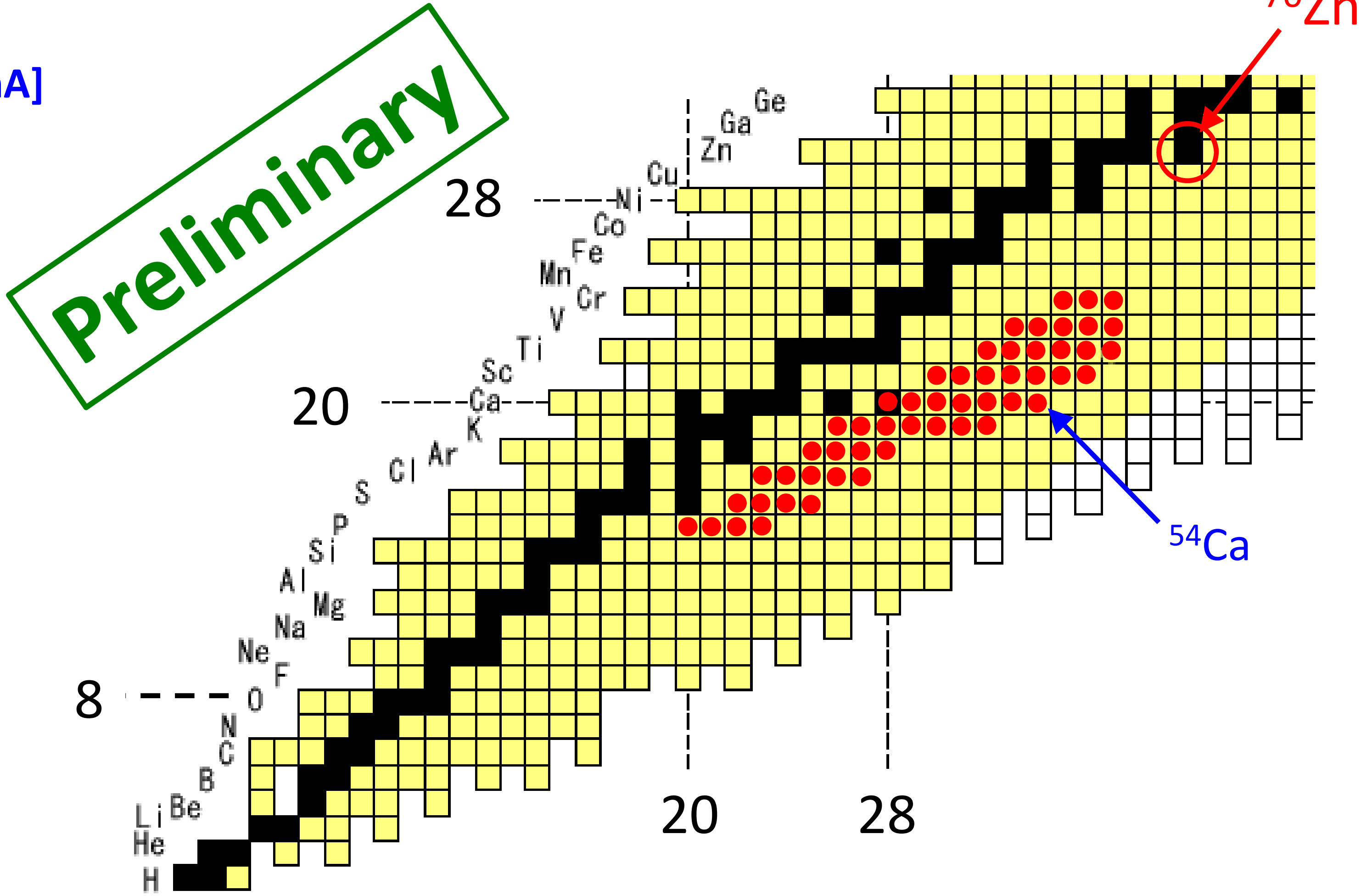
Measurements with ^{70}Zn beam

Neutron-rich isotopes by projectile fragmentation

Yields of neutron-rich RI beams using a ^{70}Zn beam at 345 MeV/u

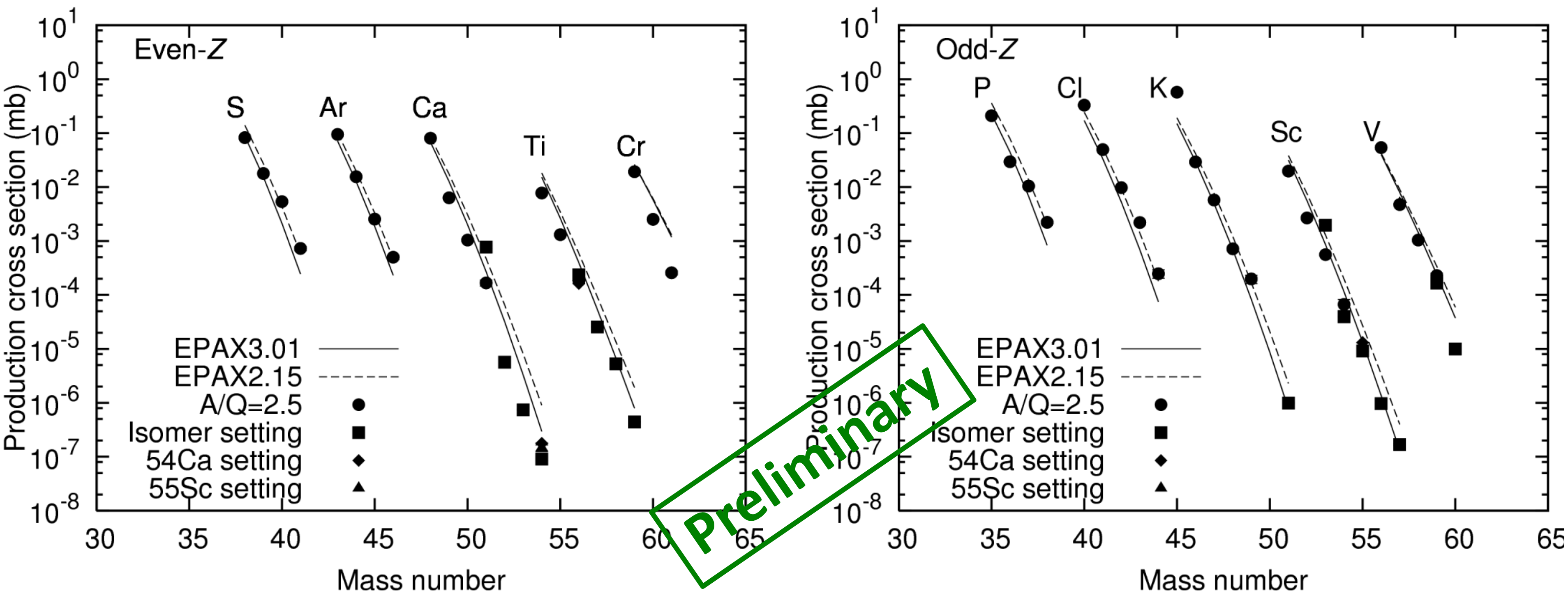
Yields [cps/pnA]

^{51}K	0.35
^{52}Ca	2.2
^{53}Ca	0.51
^{54}Ca	0.11
^{55}Sc	13
^{56}Sc	0.85
^{57}Sc	0.12
^{56}Ti	140
^{57}Ti	5.9
^{58}Ti	3.7
^{59}Ti	0.35
^{60}V	2.2



Recent ^{70}Zn-beam Intensity : ~70 pnA (Jul 2012)

Measured production cross sections comparison with EPAX 3.01 & 2.15 (^{70}Zn 345 MeV/u + Be)

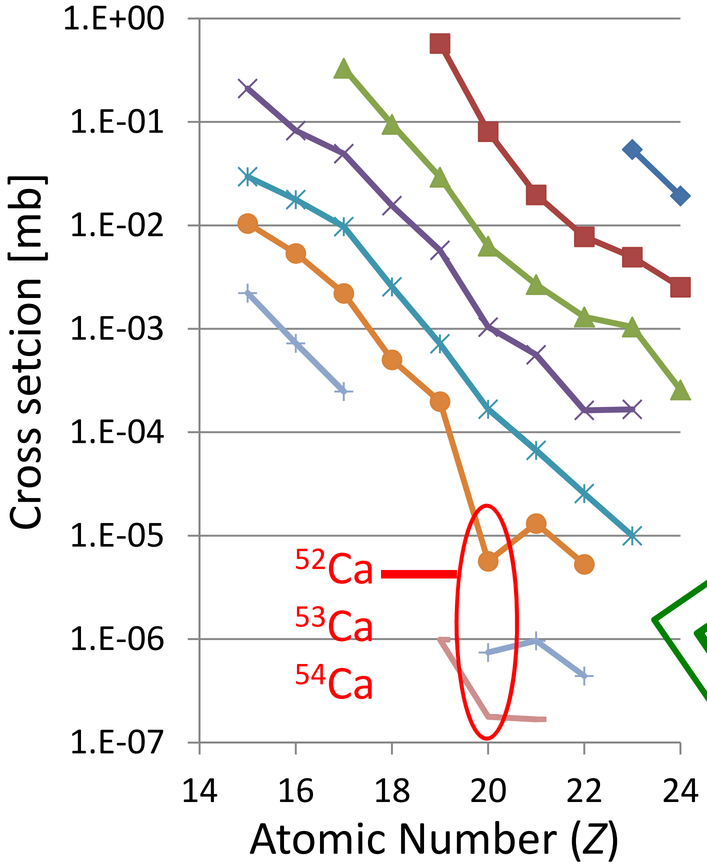


- Overall, good agreement between the experimental cross section and the EPAX parameterizations.
- For $Z < 20$ region, EPAX 2.15 estimates the cross sections well. EPAX 3.01 underestimates them.
- for $Z > 20$ region, EPAX 3.01 estimates them well. EPAX 2.15 overestimates them.
- For $^{52\text{-}54}$Ca, the experimental cross sections are less than the EPAX 3.01 estimations.

→ Next page.

Dip at Ca isotopes

^{70}Zn + Be (345 MeV/u)



Preliminary

data are connected by lines of constant *N*-2*Z* (*A*-3*Z*).

- There is a similar dip at $^{52\text{-}54}$Ca.

Cf) ^{82}Se + Be (139 MeV/u)
O. B. Tarasov, *et.al*,
PRC 87, 054612 (2013)

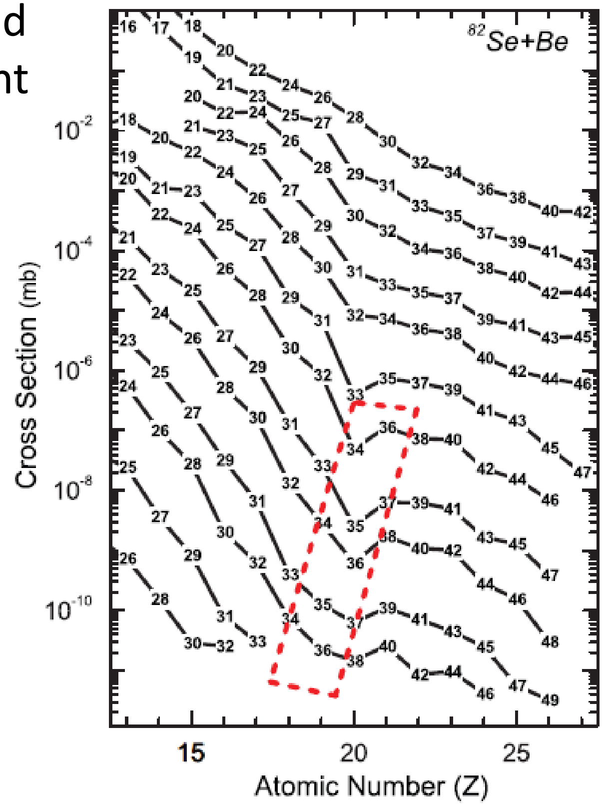


FIG. 9. (Color online) Production cross section versus atomic number (Z) for fragments from the reaction of ^{82}Se with beryllium targets. Lines are connected according to constant $N - 2Z$, while labels represent the neutron number. Reactions resulting in neutron pickup are omitted. The red dashed quadrangle is explained in the text.

Two-neutron separation energy

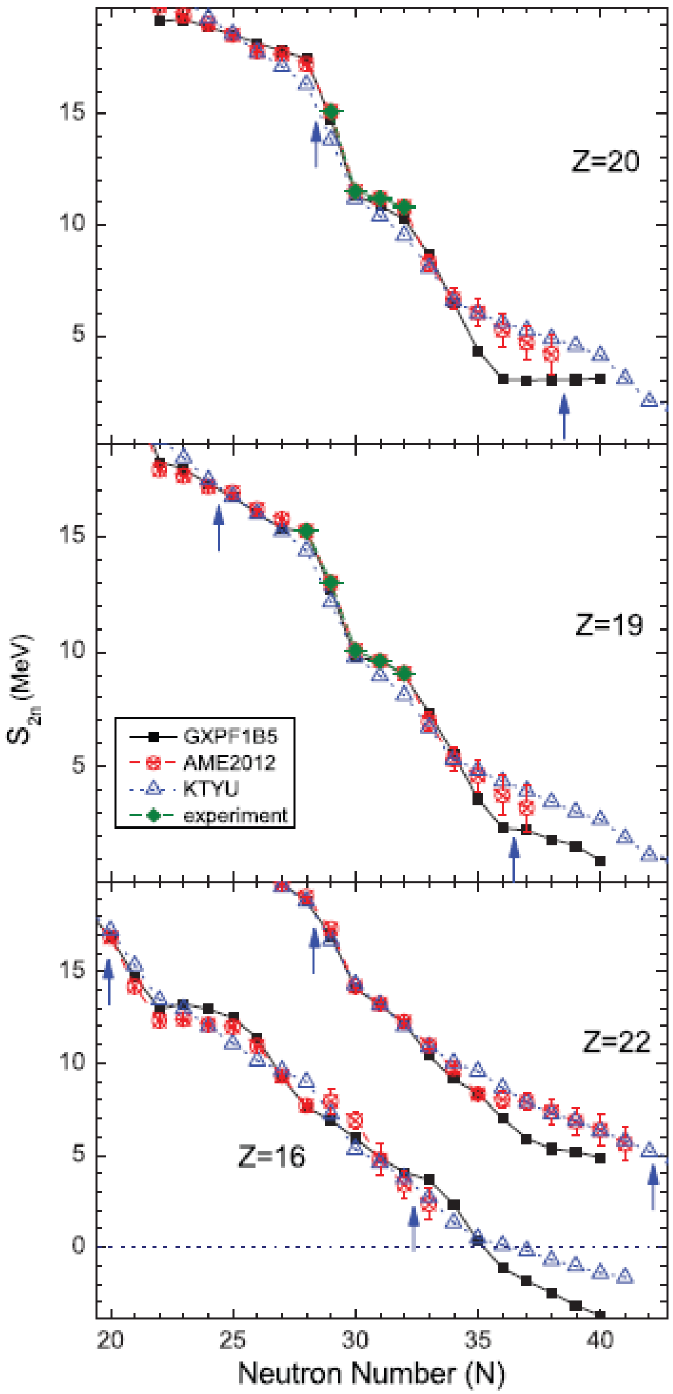


FIG. 8. (Color online) The two-neutron separation energy S_{2n} deduced from mass values as a function of the neutron number for calcium (top), potassium (middle), and sulfur and titanium isotopes (bottom). Those from experimental mass values [42] are shown by diamonds and those from AME2012 [43] by crossed circles. Results based on the full pf-shell phenomenological GXPF1B5 [29] interaction and the KTYU mass model [7] are shown by solid squares and empty triangles, respectively. Arrows show regions of isotopes whose measured cross sections are shown in Fig. 7.

O. B. Tarasov, *et.al*, PRC 87, 054612 (2013)

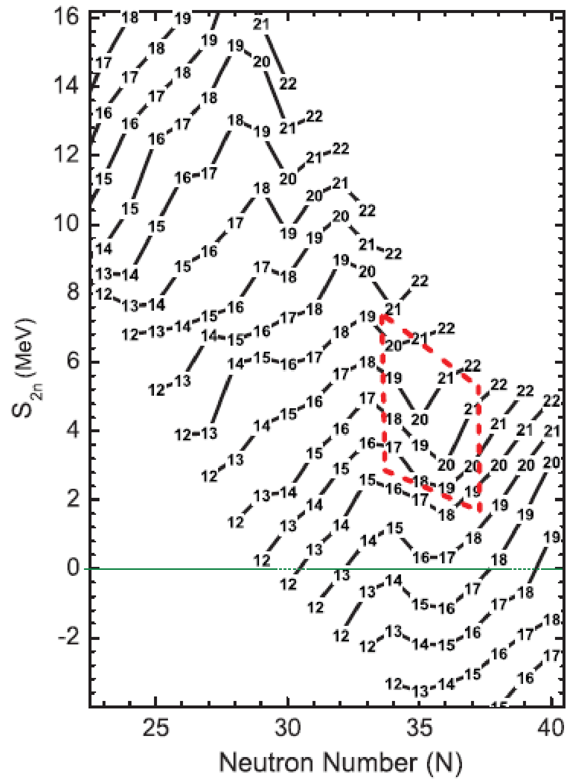


FIG. 10. (Color online) Two-neutron separation energy (S_{2n}) versus neutron number (N) for elements $12 \leqslant Z \leqslant 22$. Values are calculated using results from the GXPF1B5 [29] model. Labels in the lines show the atomic numbers of the nuclei. The red dashed quadrangle is explained in the text.

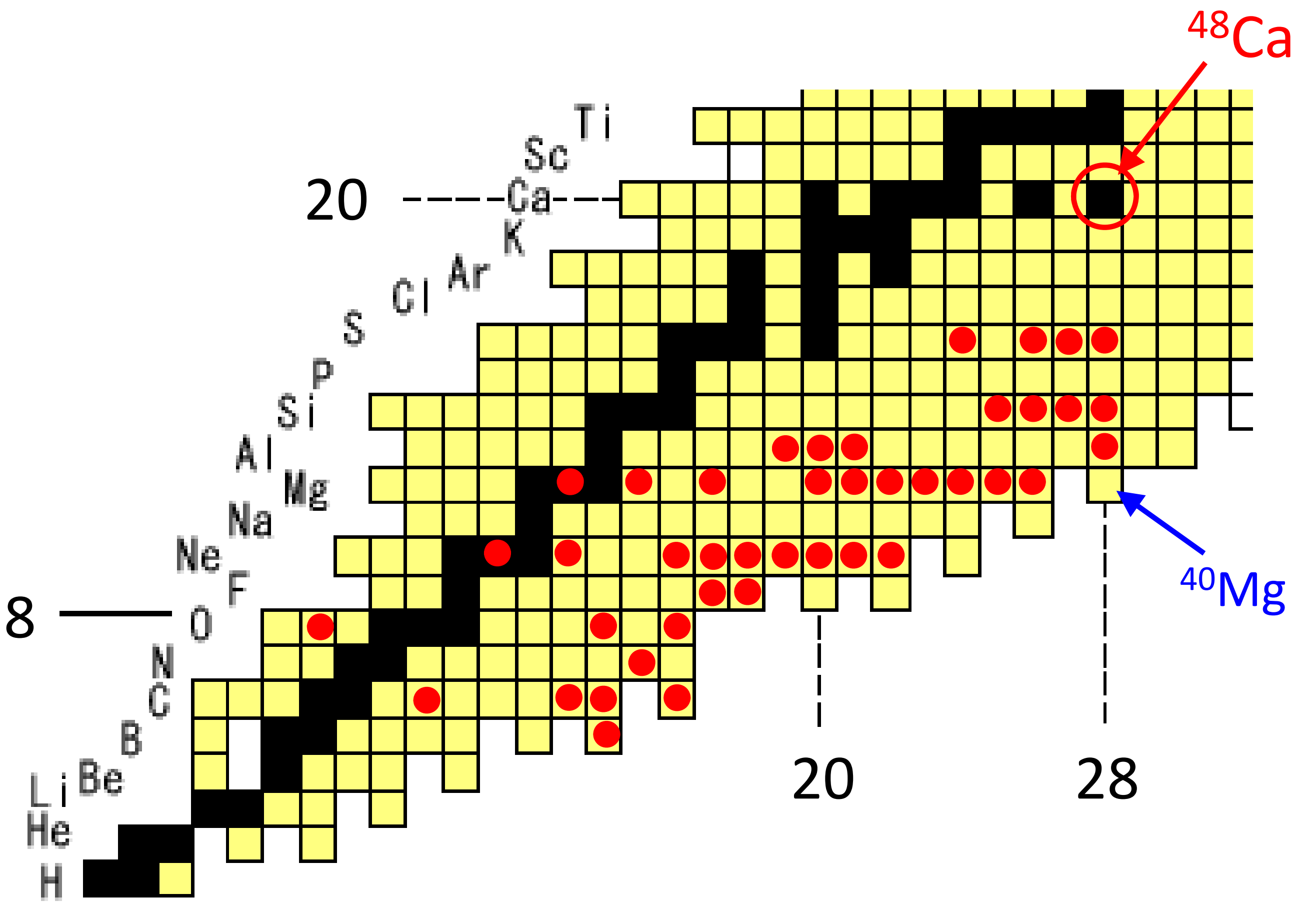
RIKEN NiSHiNA CENTER

Measurements with ^{48}Ca beam
Neutron-rich isotopes by projectile fragmentation

Yields of neutron-rich RI beams using a ^{48}Ca beam at 345 MeV/u

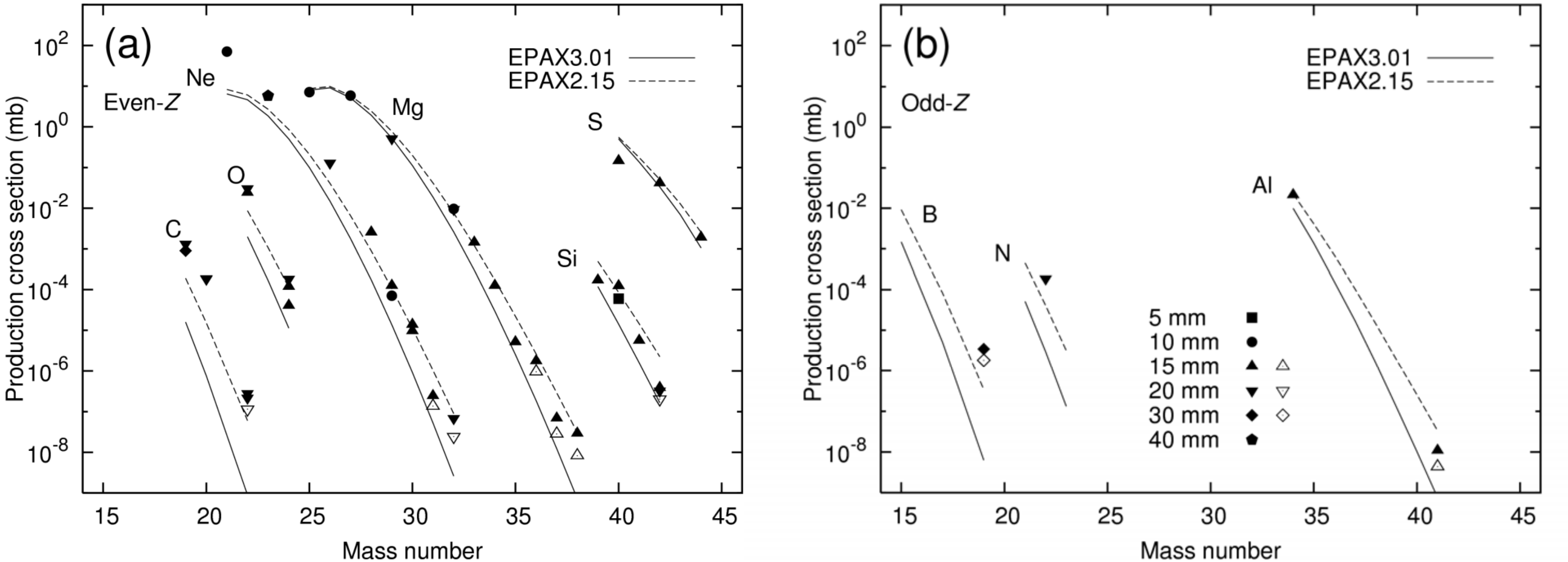
Yields [pps/100 pnA]

^{19}B	5.5
^{22}C	7.0
^{22}N	4000
^{24}O	1300
^{32}Ne	3.4
^{38}Mg	1.5
^{41}Al	0.63
^{42}Si	25
^{44}S	30000



Recent ^{48}Ca-beam Intensity : ~400 pnA (May 2012)

Measured production cross sections compared with EPAX 3.01 & 2.15 (^{48}Ca 345 MeV/u + Be)



Open symbols: cross sections with the correction for the secondary reaction effect in the target (only for the nuclides whose augmentation factors are more than 1.6.)

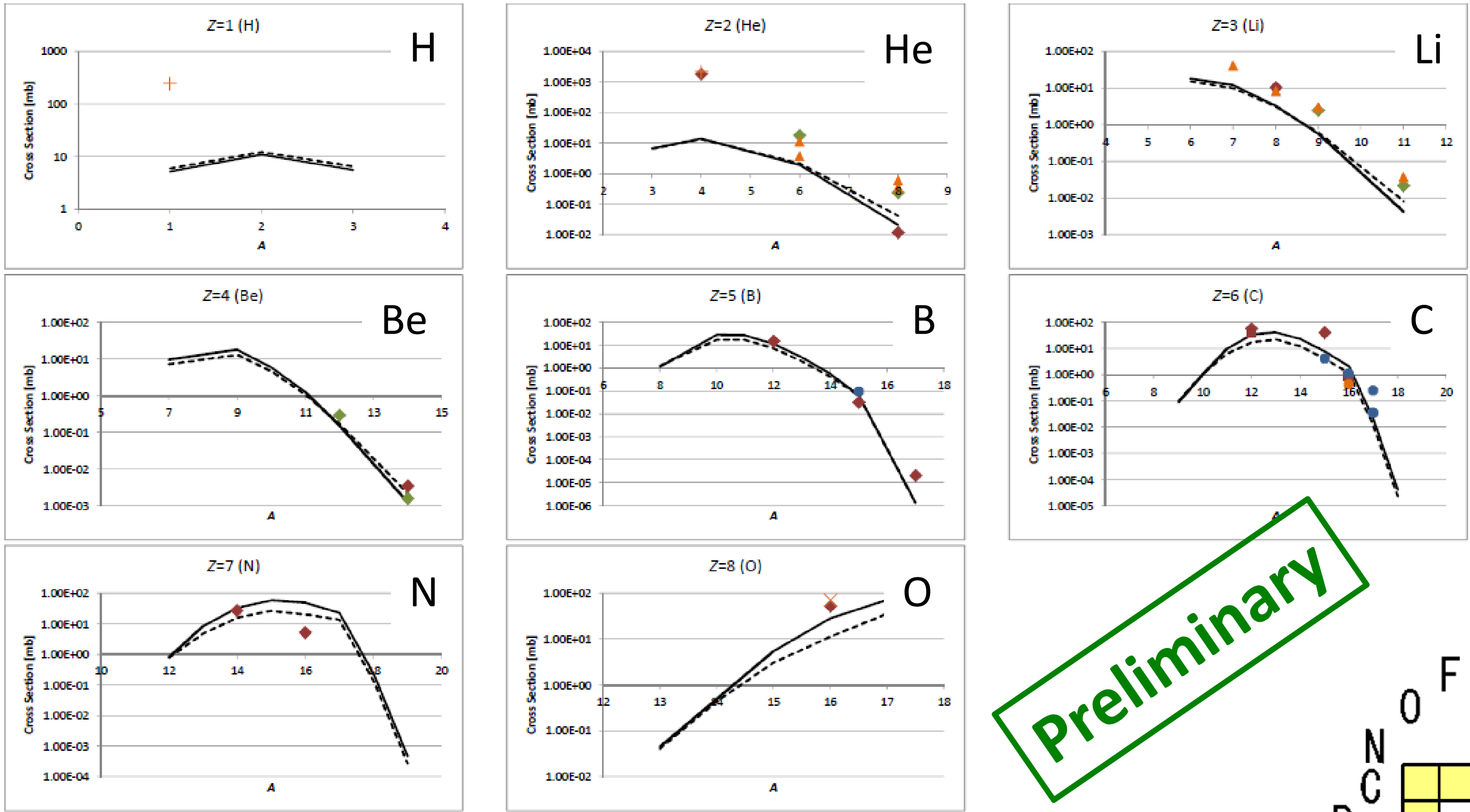
- Fairly good agreement between the experimental cross sections and EPAX 2.15.
- EPAX 3.01 underestimates the cross sections.

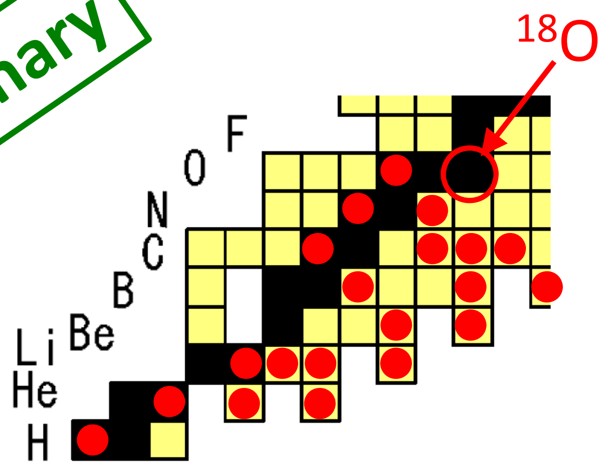
Modification of EPAX3 from EPAX2

The c.s. of very neutron-rich fragments from medium-mass and heavy projectile were modified, which were overestimated by EPAX2. At the same time, the good agreement of EPAX2 for the neutron-deficient side is maintained.

Measurements with ^{18}O beam
Neutron-rich isotopes by projectile fragmentation

Measured production cross sections compared with EPAX 3.01 & 2.15 (^{18}O 230, 250, 294, 345 MeV/u + Be)





- Discrepancy was observed in some cases.

Summary for the cross sections of RIs produced by projectile fragmentation

- Production cross sections of various radioactive isotopes were measured using with the BigRIPS separator at RIBF and compared with the EPAX parameterizations.
  - RIs were produced from ^{124}Xe (345 MeV/u), ^{70}Zn (345 MeV/u), ^{48}Ca (345 MeV/u), and ^{18}O (230, 250, 294, 345 MeV/u).
- Neutron-deficient isotopes from ^{124}Xe beam at 345 MeV/u.
  - EPAX 3.01 estimates them well around the near stable region, while it overestimates them in more neutron-deficient region and higher-*Z* region.
  - The low mom. tails were measured. "coef" of 1.9 gives the best results in LISE++.
  - Discrepancy of the ^{100}Sn c. s. between the RIKEN data and the GSI data.
- Neutron-rich isotopes from ^{70}Zn beam at 345 MeV/u.
  - EPAX parameterizations estimates the c. s. well except the very neutron-rich Ca.
  - A dip at very neutron-rich Ca isotopes was observed.
- Neutron-rich isotopes from ^{48}Ca beam at 345 MeV/u.
  - EPAX 2.15 estimates the c. s. fairly well.
  - EPAX 3.01 underestimates the c. s.
- Neutron-rich isotopes from ^{18}O beams.
  - Discrepancy was observed between the c. s and the EPAXs.

Section 2

New isotopes
in the ^{124}Xe beam experiment

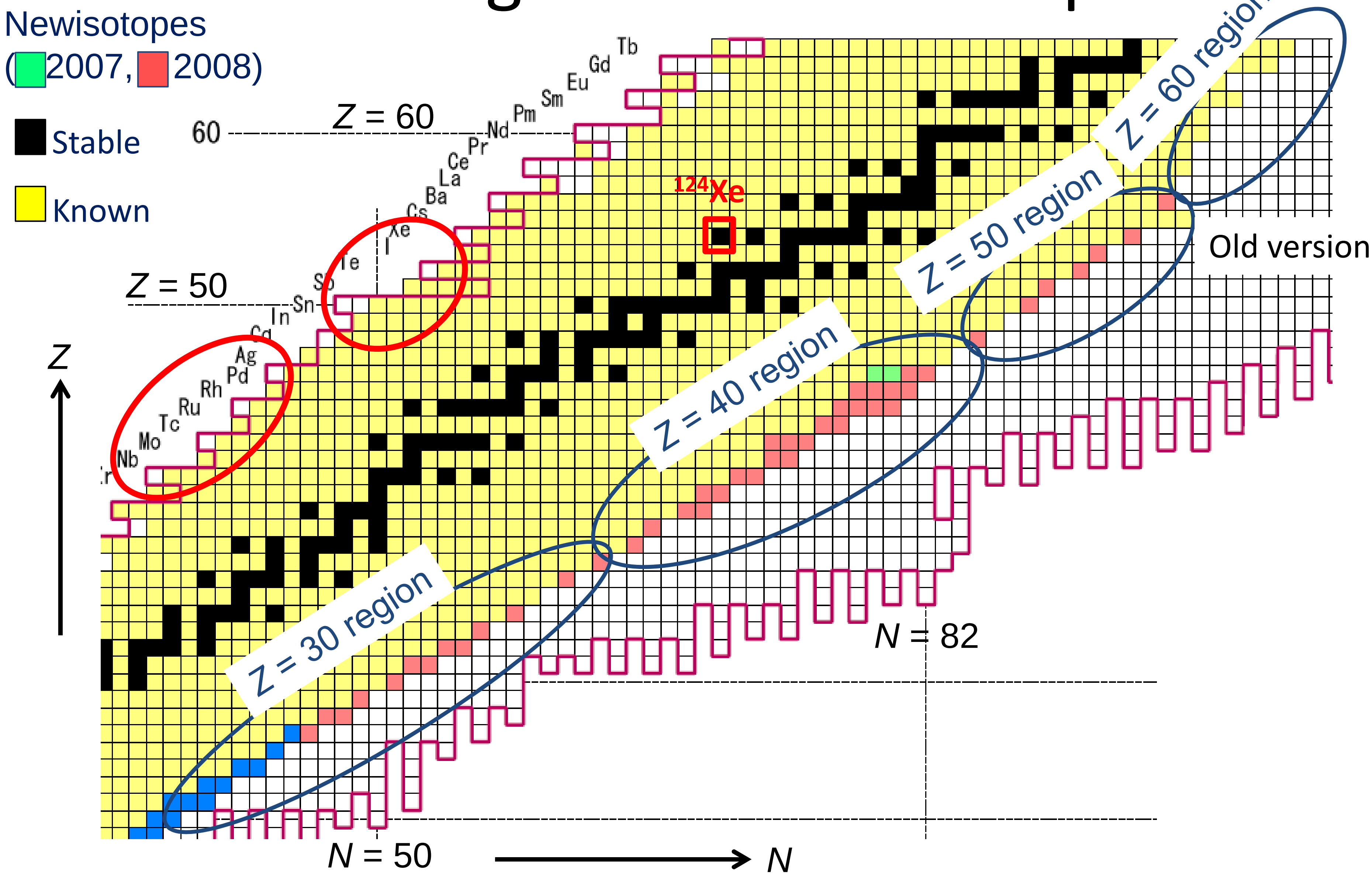
Introduction

- New isotope search → The frontier of exotic nuclei far from the stability
  Expanding of the study region
- Production of neutron-deficient nuclei : near proton drip line
  - RI-beam production from ^{124}Xe beam at 345 MeV/u.
  - Separation and identification at BigRIPS.
    High A/Q resolution by "trajectory reconstruction".
  - PID confirmation by known isomeric γ rays.

New isotope search at RIBF

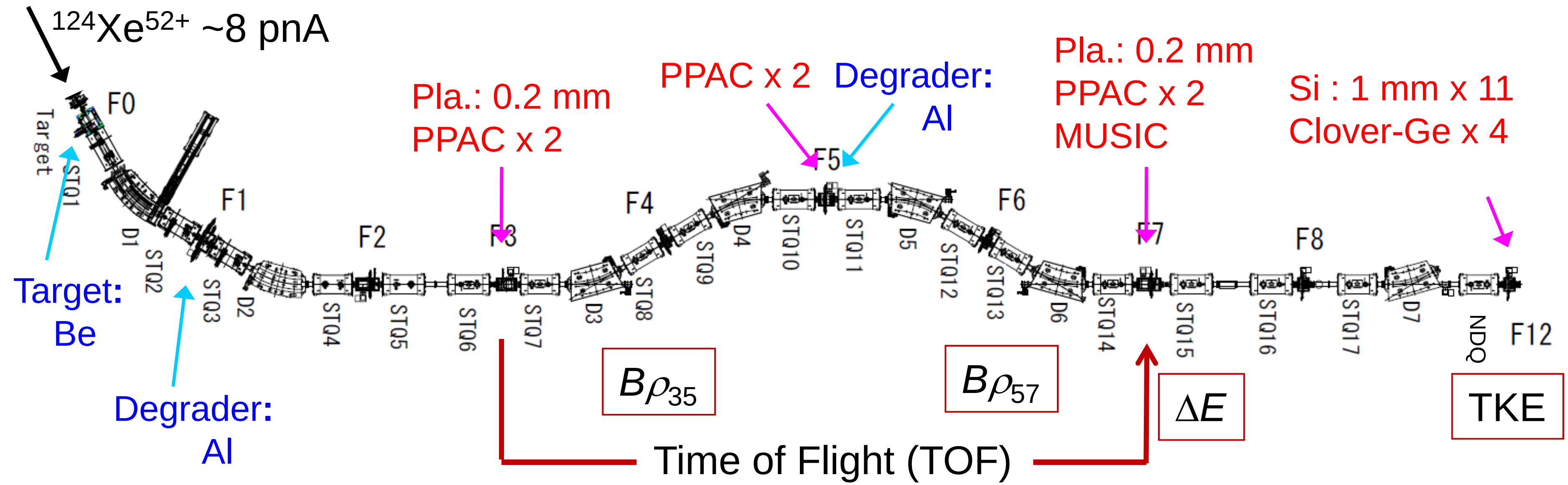
Year	Beam intensity	New isotopes
2007	0.006 pnA (^{238}U)	2 : ^{125}Pr, ^{126}Pr
2008	0.2 pnA (^{238}U)	45 : Mn(Z=25) ~ Ba(Z=56)
2011	0.5 pnA (^{238}U)	>20 : Z~60 (preliminary)
2011	8 pnA (^{124}Xe)	NEW!!

Search region for new isotopes



Nuclear chart

Experimental setup



RI production & separation: F0-F2

- Projectile fragments
- Separation using A/Q and R(range) of RIs
- Two stage separation with the degraders at F1 & F5

PID (A/Q): F3-F7

$B\rho_{35}$, $B\rho_{57}$,TOF

- $B\rho_{35}$, $B\rho_{57}$,TOF → A/Q

$TOF_{37} = L_{35}/\beta_{35}c + L_{57}/\beta_{57}c$

$A/Q = B\rho_{35} / c\beta_{35}\gamma_{35}$

$A/Q = B\rho_{57} / c\beta_{57}\gamma_{57}$

PID (Z,A): F7,F12

ΔE, TKE, γ-ray

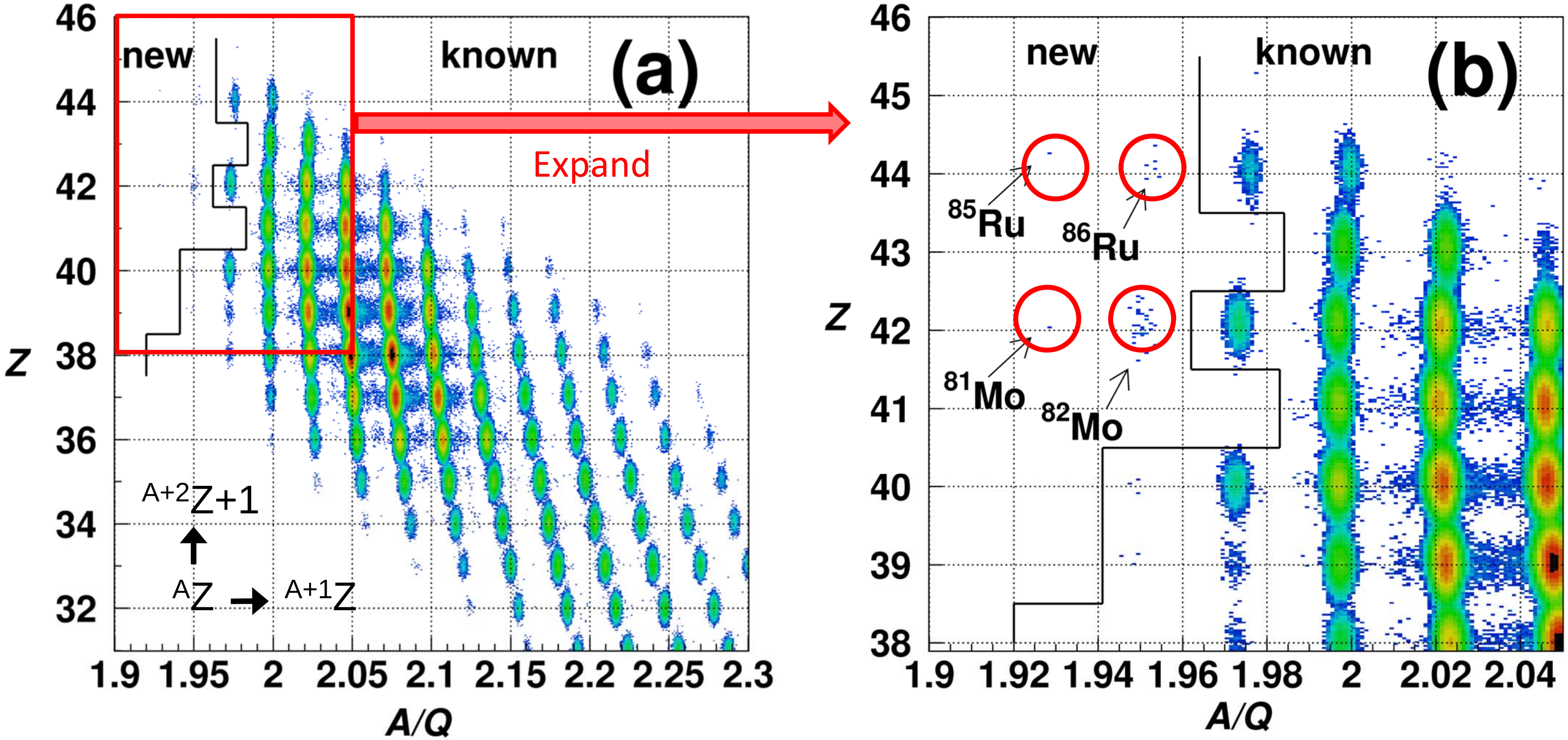
- ΔE → Z
- TKE, TOF → A
- TKE, TOF, $B\rho$ → Q
- γ-ray → isomers

BigRIPS settings for new isotope search

- Two settings

Setting	^{85}Ru setting (Z=41-46)	^{105}Te setting (Z=52-54)
Isotope tuned	$^{85}Ru^{44+}$	$^{105}Te^{52+}$
F0 target (mm^t)	Be 4.03	Be 4.03
$B\rho_{01}$ (Tm)	5.114	5.300
$B\rho_{35}$ (Tm)	4.534	4.596
F1 degrader	Al 2.85 mm^t, 3.6 mrad	Al 2.85 mm^t, 3.6 mrad
F5 degrader	Al 1.97 mm^t, 1.6 mrad	Al 1.97 mm^t, 1.6 mrad
F1 slit	$\Delta p/p$: +/-2.0%	$\Delta p/p$: -2.0~+1.5%
F2 slit (mm)	+/-20	-15~+20
F5 slit	fully open	fully open
F7 slit (mm)	+/-20	+/-10
Beam intensity (pnA)	~ 7.6	~ 8.9
F3 rate (pps)	~ 40k	~ 40k
F7 rate (pps)	~ 1.5k	~ 1.0k

^{85}Ru setting



A/Q resolution (r.m.s.): 0.061%

Z resolution (r.m.s.): 0.40 % @ Zr (*Z*=40) isotopes

TOF(F0-F7): ~430 ns

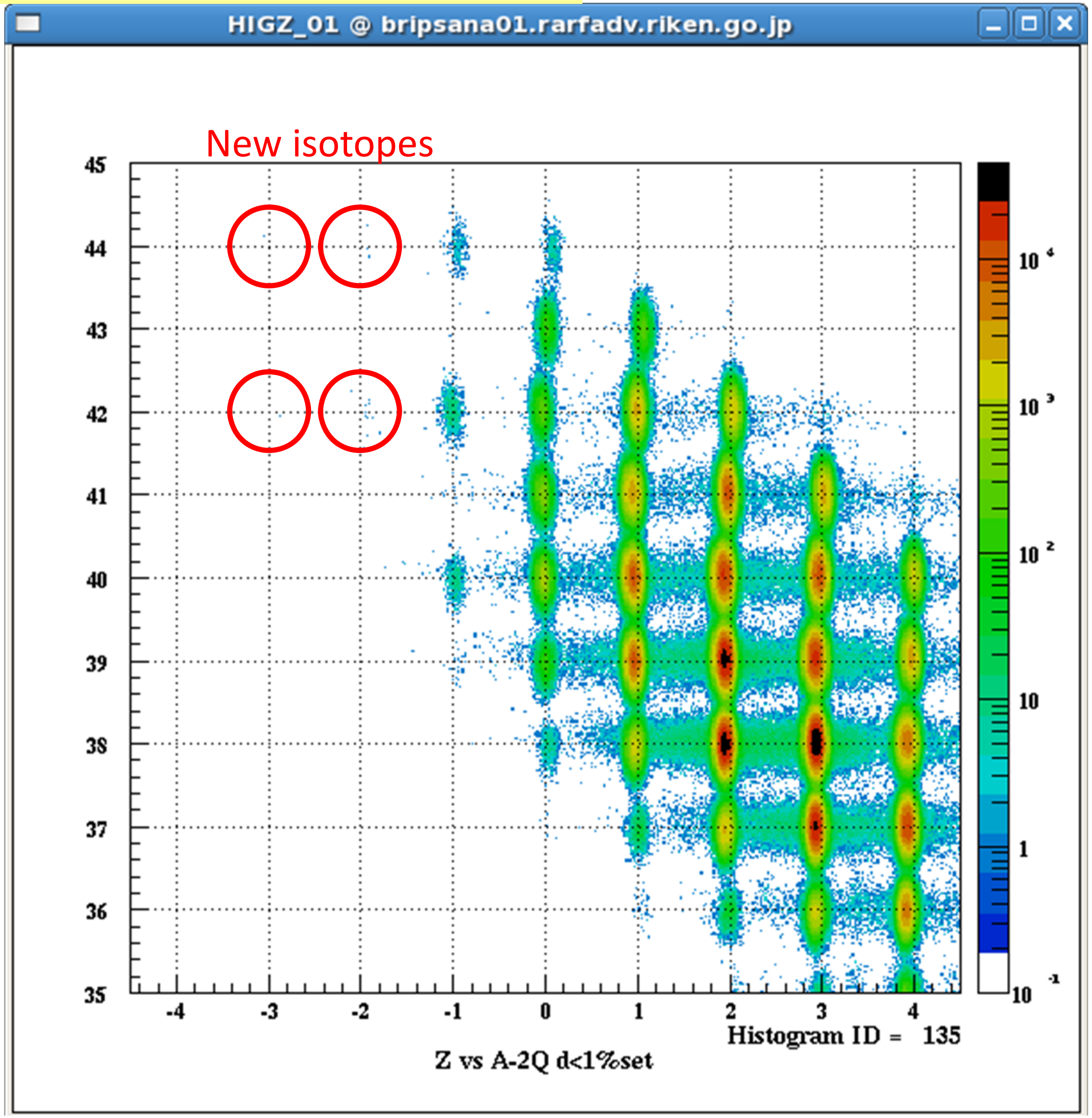
- The known limits are shown by solid lines.

New isotopes identified in this work: ^{85}Ru, ^{86}Ru, ^{81}Mo, ^{82}Mo

^{85}Ru setting (Z vs A-2Q plot)

- Full stripped events are shown in this plot.
- *A* is deduced from the TKE measured with SSD at F12.

85Ru: 1	86Ru: 3
81Mo: 1	82Mo: 11



Unbound nuclei of Ru and Mo isotopes

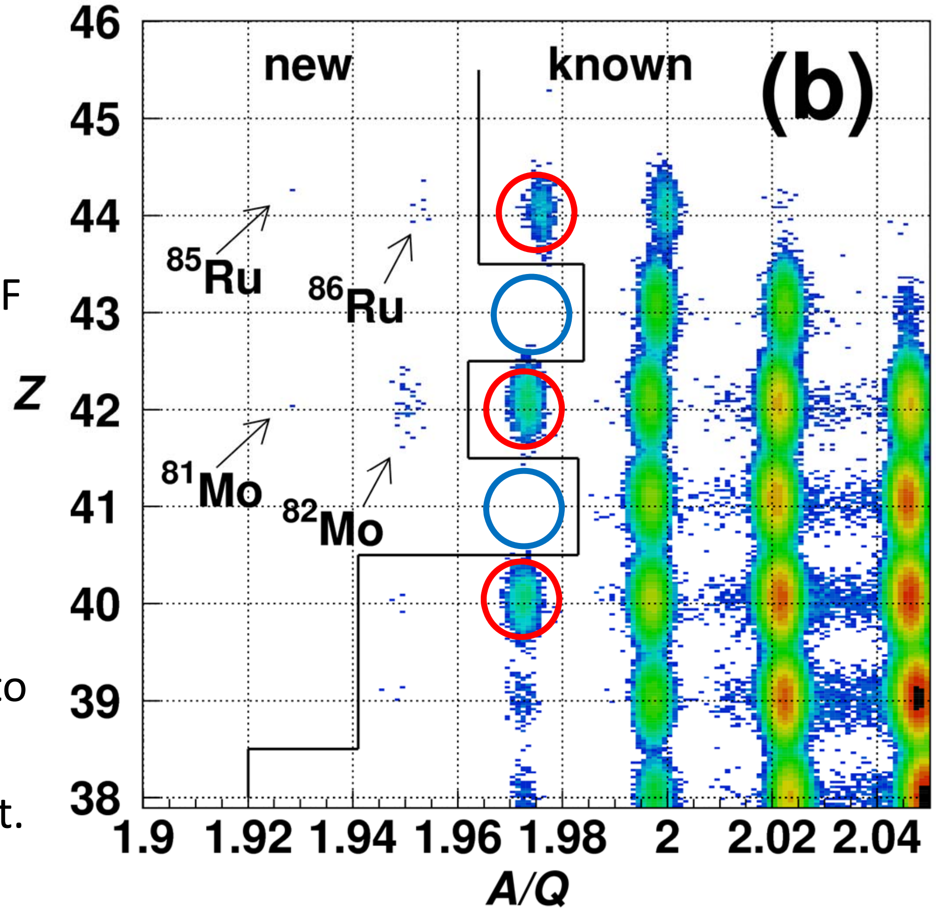
- On the line of *A* = 2*Z*-1,
  - ^{87}Ru, ^{83}Mo, ^{79}Zr : observed
  - ^{85}Tc, ^{81}Nb: absent

→ There live times are short compared to the TOF (~440 ns).

- Consistent with the results by Z. Janas, *et al*, Phys. Rev. Lett. 82, 295 (1999).

- The upper limits of the half lives.
  - Considering the yields expected relative to the neighboring isotopes.
  - Assuming the observation limit of 1 count.
- ^{85}Tc : 42 ns, ^{81}Nb: 38 ns

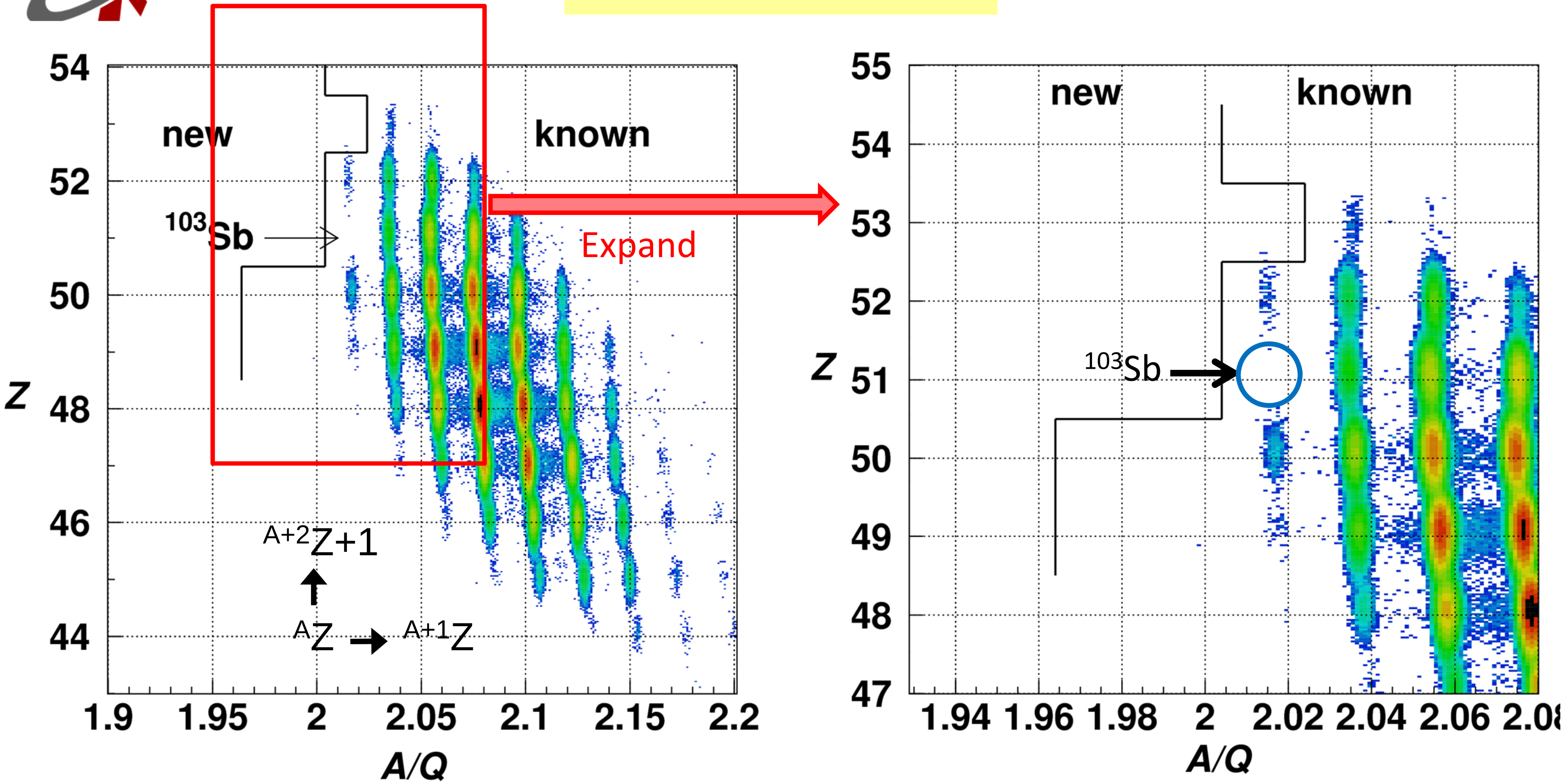
→ They are outside of the proton drip line.



- On the other hand, the experimental yield of the new isotopes ^{86}Ru and ^{82}Mo are almost the same with the expected yield.

→ The half lives of them are long enough compared to the TOF (~440 ns)

^{105}Te setting



A/Q resolution (r.m.s.): 0.054%

Z resolution (r.m.s.): 0.39 % @ Zr (*Z*=40) isotopes

TOF(F0-F7): ~440 ns

- The known limits are shown by solid lines.

No new isotopes in this region.

Unbound nuclei of Sb isotopes

- Upper limit : ~55ns
  - The number at F0 : 413 counts

    (expected yield of ^{103}Sb is deduced from the ones of neighboring nuclei)
  - TOF from F0 to F7 : ~440 ns

→ ^{103}Sb is outside of the proton drip line.

^{103}Sb was discovered by K. Rykaczewski, *et. al.* in 1995.
(observed after TOF of 1.5 μs)
K. Rykaczewski, *et al*, Phys. Rev. C, 52, R2310 (1995)

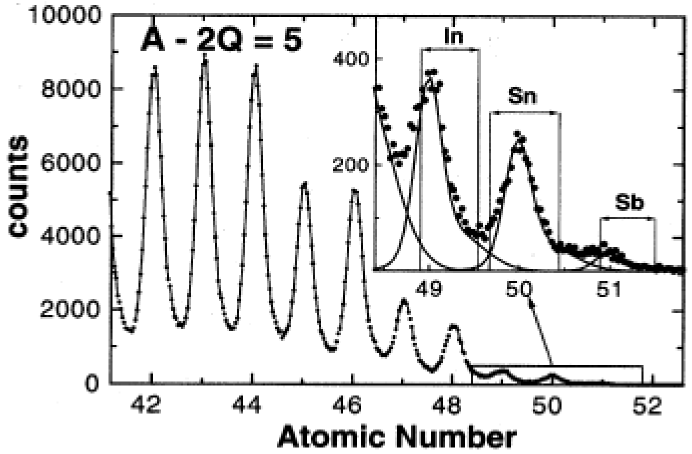
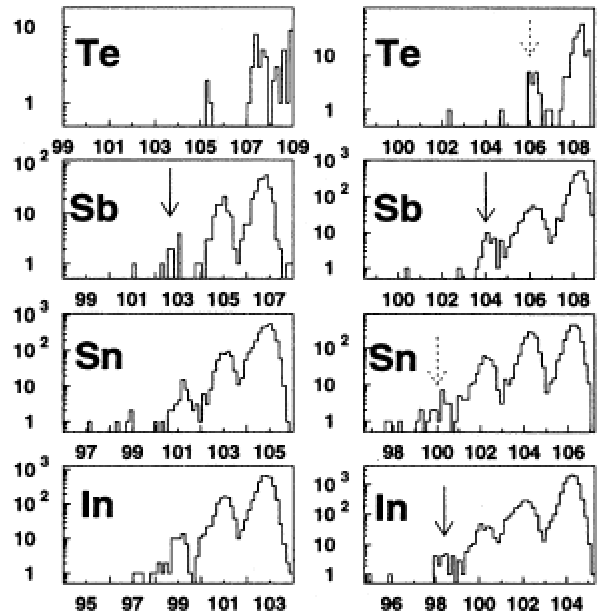
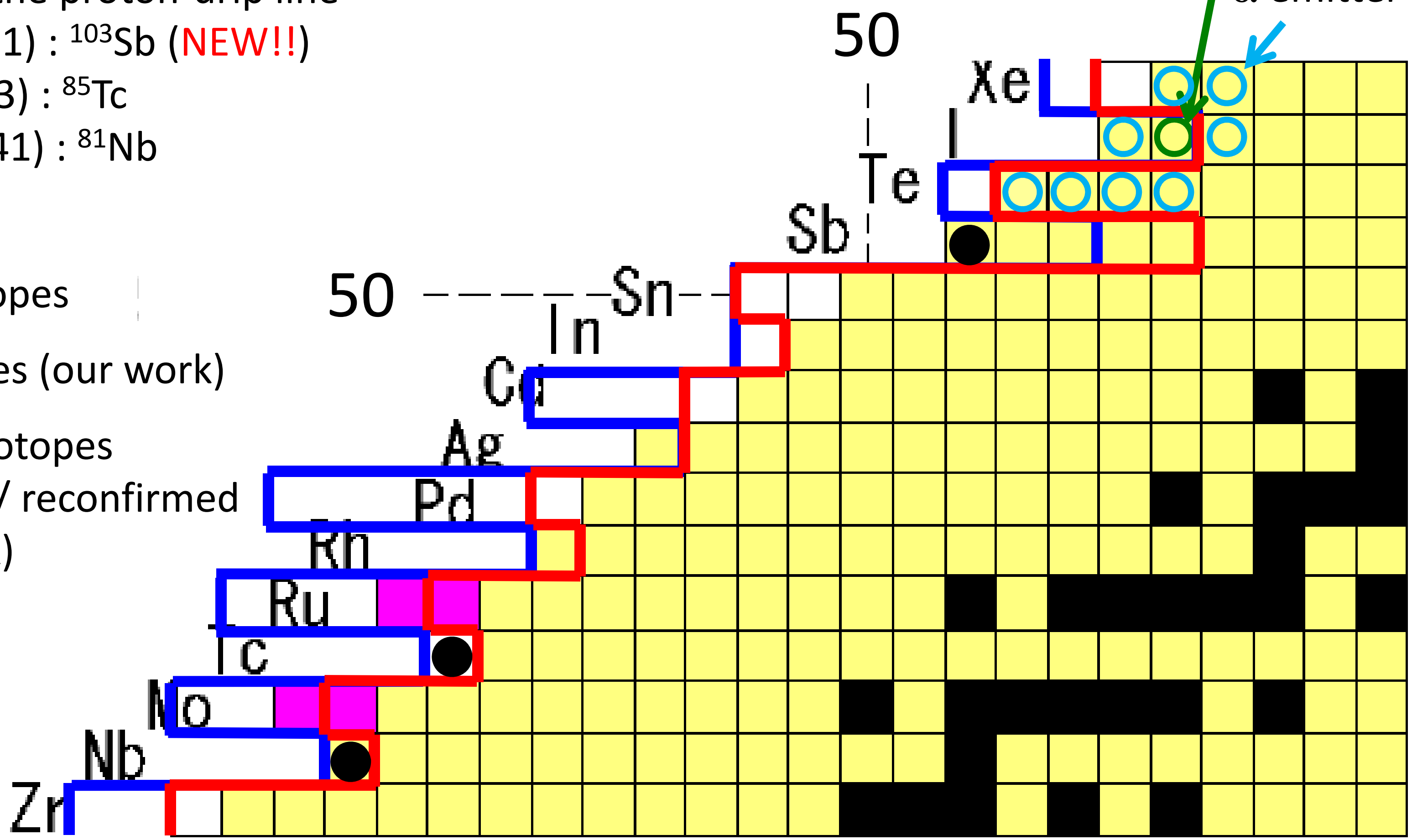


FIG. 2. The Z distribution of heavy fragments with mass (A) and charge state (Q) corresponding to $A-2Q=5$ (e.g., $^{103}Sb^{+49}$) in the experiment with the 63 MeV/nucleon ^{112}Sn beam. A fit to the Z distribution, based on a "Z-response function" determined experimentally with γ-correlated events, is displayed in the inset for indium, tin, and antimony. Also the gates applied to select events belonging to these elements (keeping the contamination on a few percent level) are indicated.



Summary on search for new isotopes around the proton-drip line

- New isotopes
  - Four new isotopes : ^{81}Mo, ^{82}Mo (*Z*=42), ^{85}Ru, ^{86}Ru (*Z*=44) (NEW!!)
- Outside of the proton-drip line
  - Sb (*Z*=51) : ^{103}Sb (NEW!!)
  - Tc (*Z*=43) : ^{85}Tc
  - Nb (*Z*=41) : ^{81}Nb



Known isotopes

New isotopes (our work)

Unbound isotopes (confirmed / reconfirmed in our work)

KTUY05 model (H. Koura *et al*, Prog. Theor. Phys. 113, 305 (2005).)

HFB-14 model (S. Goriely, M. Samyn, J.M. Pearson, Phys. Rev. C 75, 064312 (2007).)

Section 3

Production rate of RIs produced by the in-flight fission of ^{238}U

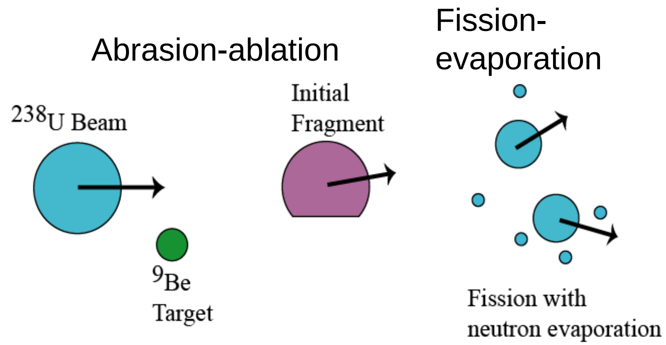
- Be-target (Abrasion Fission)
- Pb / W-target (AF + Coulomb Fission)

LISE++ Abrasion Fission (AF) model

Oleg Tarasov, NSCL/MSU

Three excitation energy regions (3 EERs) method

- Low excitation region: fission barrier < E^* < 40 MeV
- Middle excitation region: 40 MeV < E^* < 180 MeV
- High excitation region: 180 MeV < E^*



(from Tony Nettleton)

Parameters for ^{238}U + Be

	Low	Middle	High
fissile	$^{236}_{92}$U	$^{226}_{90}$Th	$^{220}_{84}$Ra
E^* MeV	23.5	100	250
σ mb	200	500	350

The parameters here are the standard ones in the LISE++ manual, and determined so as to fit the GSI cross section data

^{238}U(750 MeV/u) + Be: Z=20-46, σ >~ 200 pb

M. Bernas *et al*., Nucl. Phys. A616(1997)352.

M. Bernas *et al*., Phys. Lett. B415(1997)111.

Parameters for ^{238}U + Pb

	Low	Middle	High
fissile	$^{238}_{92}$U	$^{230}_{90}$Th	$^{214}_{84}$Po
E^* MeV	17.3	100	300
σ mb	2280*	500	1300

* includes coulomb fission cross section

^{238}U(1 GeV/u) + Pb: Z=31-59, σ >~ 100 μb

T. Enqvist *et al*., Nucl. Phys. A658(1999)47.

Various setting for in-flight fission of ^{238}U at 345 MeV/u

RIKEN NISHINA CENTER

setting	A			B	G1	G2	G3
Target	Be 7 mm			Pb 1.5 mm	Be 5.1 mm	Be 2.9 mm	Pb 0.95 mm + Al 0.3 mm
$B\rho$ (Tm)	7.2	7.4	7.6	7.0	7.902	7.990	7.706
Δp/p	±1%	±1%	±2%	±0.1%	±3%	±3%	±3%
Degrader	None	None	None	None	F1: 1.29 mm	F1: 2.18 mm	F1: 2.56 mm F5: 1.8 mm
F2 slit (mm)	±30	±30	±30	±50	±13.5	±15.5	±15 mm

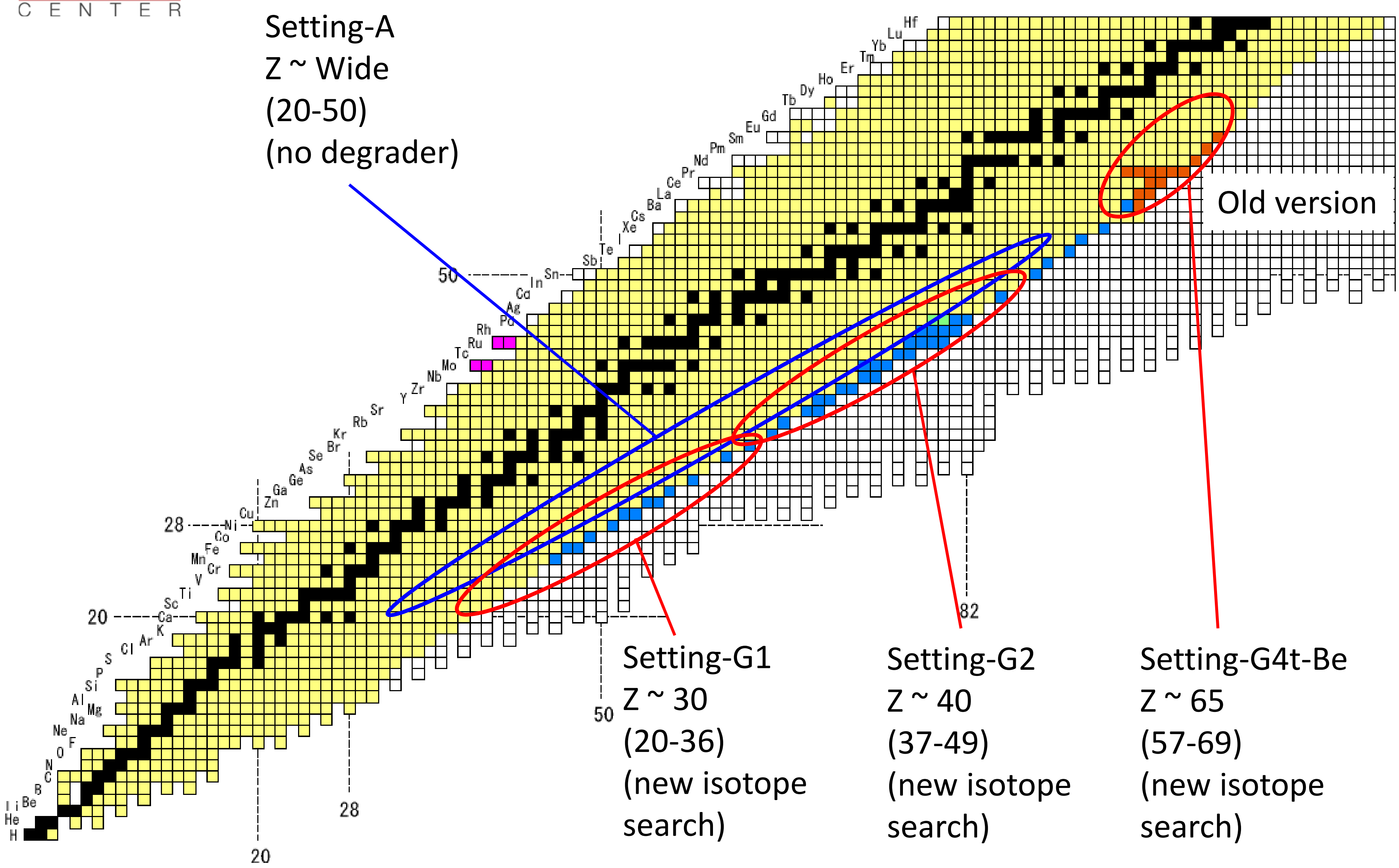
setting		G4t-Be	G4t-W				
Target	Be 4.00 mm	Be 4.93 mm	W 0.7 mm	Be 4.93 mm		W 0.7 mm	
$B\rho$ (Tm)	7.306	6.950	6.950	6.950	7.300	6.950	7.300
Δp/p	−2%/+3%	−2%/+3%	−2%/+3%	±0.1%	±0.1%	±0.1%	±0.1%
Degrader	F1: 1.27 mm F5: 1.40 mm	F1: 1.27 mm F5: 1.40 mm	F1: 1.27 mm F5: 1.40 mm	None	None	None	None
F2 slit (mm)	−3 / +15	−4 / +15	−4/+15	±120	±120	±120	±120
F7 slit (mm)	−5 / +25	±15	±15	±120	±120	±120	±120

Be target case
Abrasion Fission

Setting	A	G1	G2	G4t-Be
Region	Z ~ widely (20 - 54)	Z ~ 30 (20 - 36)	Z ~ 40 (37 - 49)	Z ~ 65 (57 - 69)
Production mechanism	Abrasion fission			
Target	Be 7.0 mm	Be 5.1 mm	Be 2.9 mm	Be 4.93 mm
$B\rho$ (Tm)	7.249	7.902	7.990	6.950
Δp/p	±1%	±3%	±3%	-2%/+3%
Degrader	No	F1: 1.29 mm	F1: 2.18 mm	F1: 1.27 mm F5: 1.40 mm
F2 slit (mm)	±30	±13.5	±15.5	-4/+15
F7 slit (mm)				±15

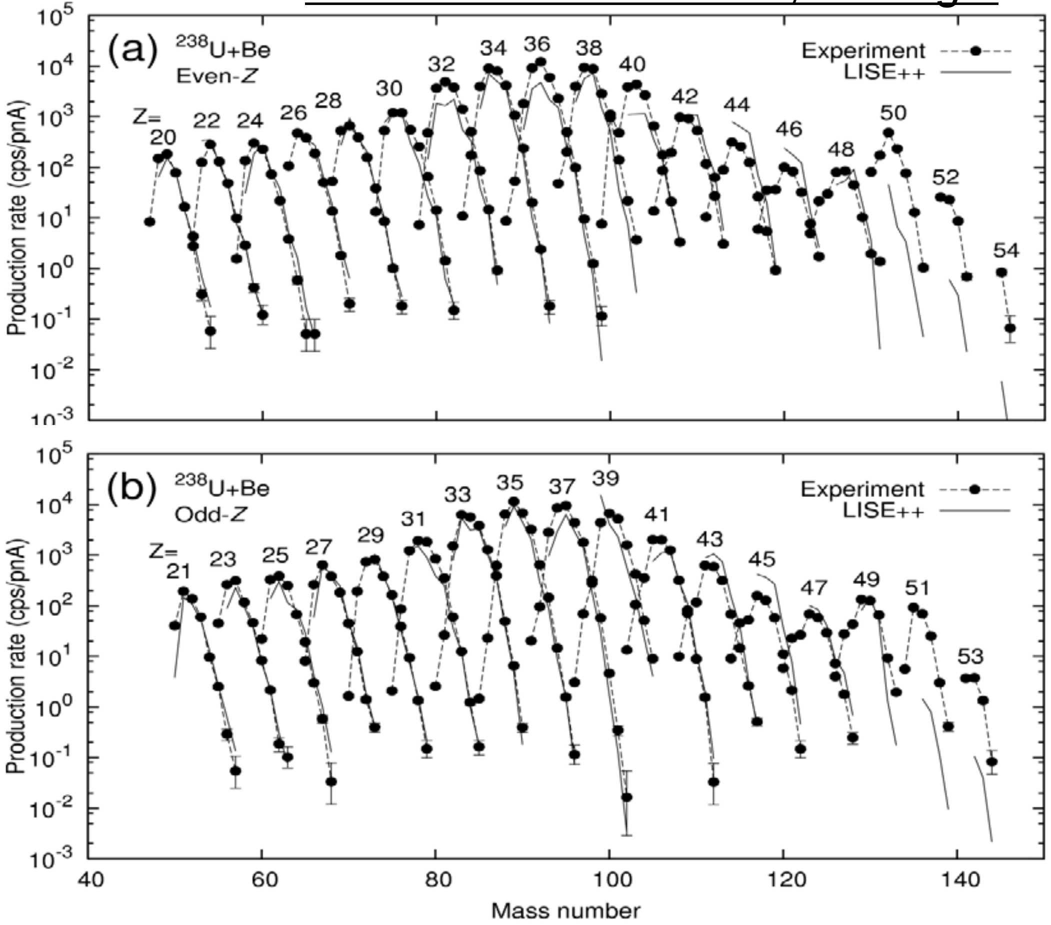
Region of the settings (Be target)

^{238}U



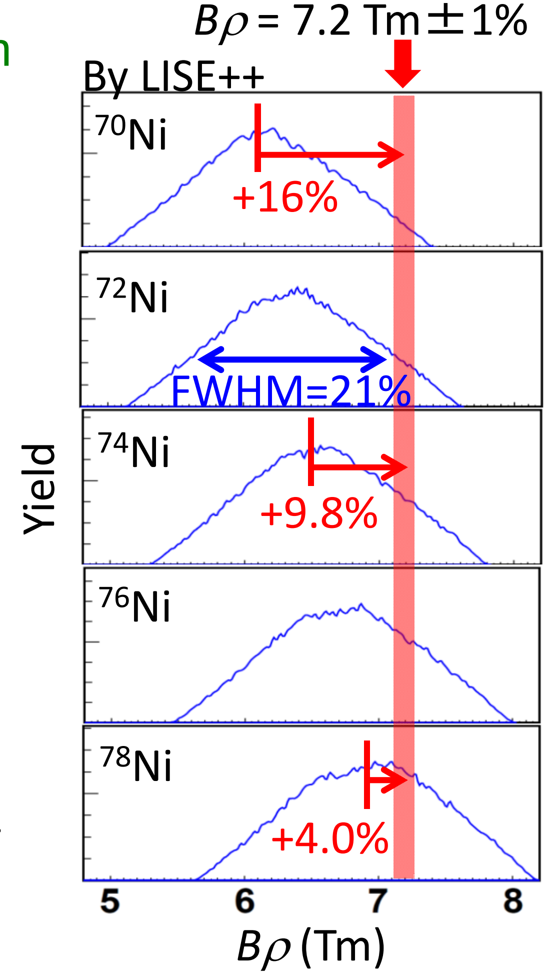
Production rates of the fragments in setting-A and comparison with LISE++ predictions by AF model

$^{238}U^{86+}$ 345MeV/u + Be, no degs.



Abrasion Fission

—— : LISE++ Ver. 8.4.1

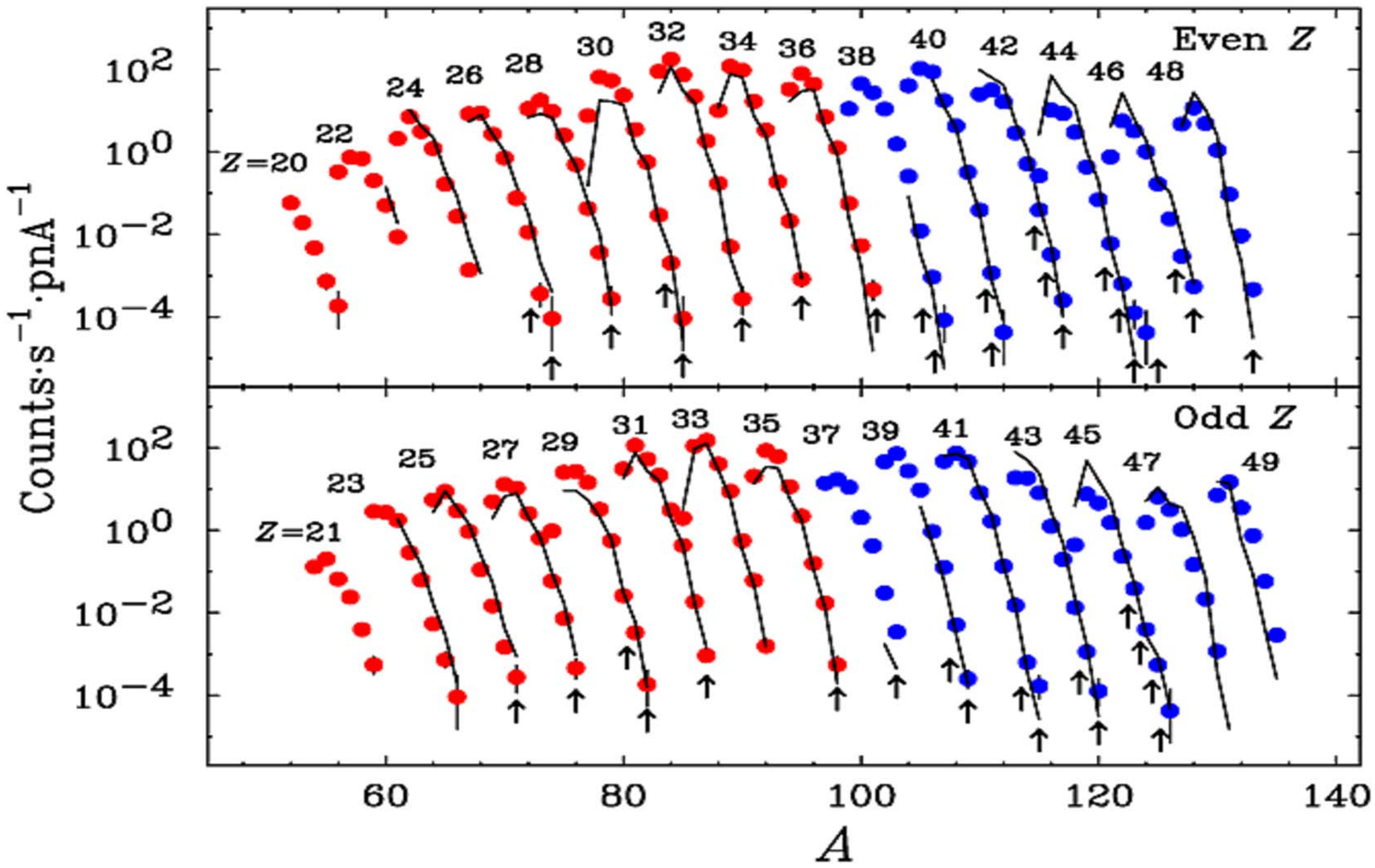


- Good agreement with LISE++ calculation with Abrasion fission model around Z = 20 - 50.
- At Z > 50 region, experimental production rates are much larger than the LISE++ calculation.

Production rates of the fragments in setting-G1 & G2 and comparison with LISE++ predictions by AF model

$^{238}U^{86+}$ 345MeV/u + Be   Abrasion fission

● Setting G1: Z~30   ● Setting G2: Z~40   —— LISE++(ver. 8.4.1)

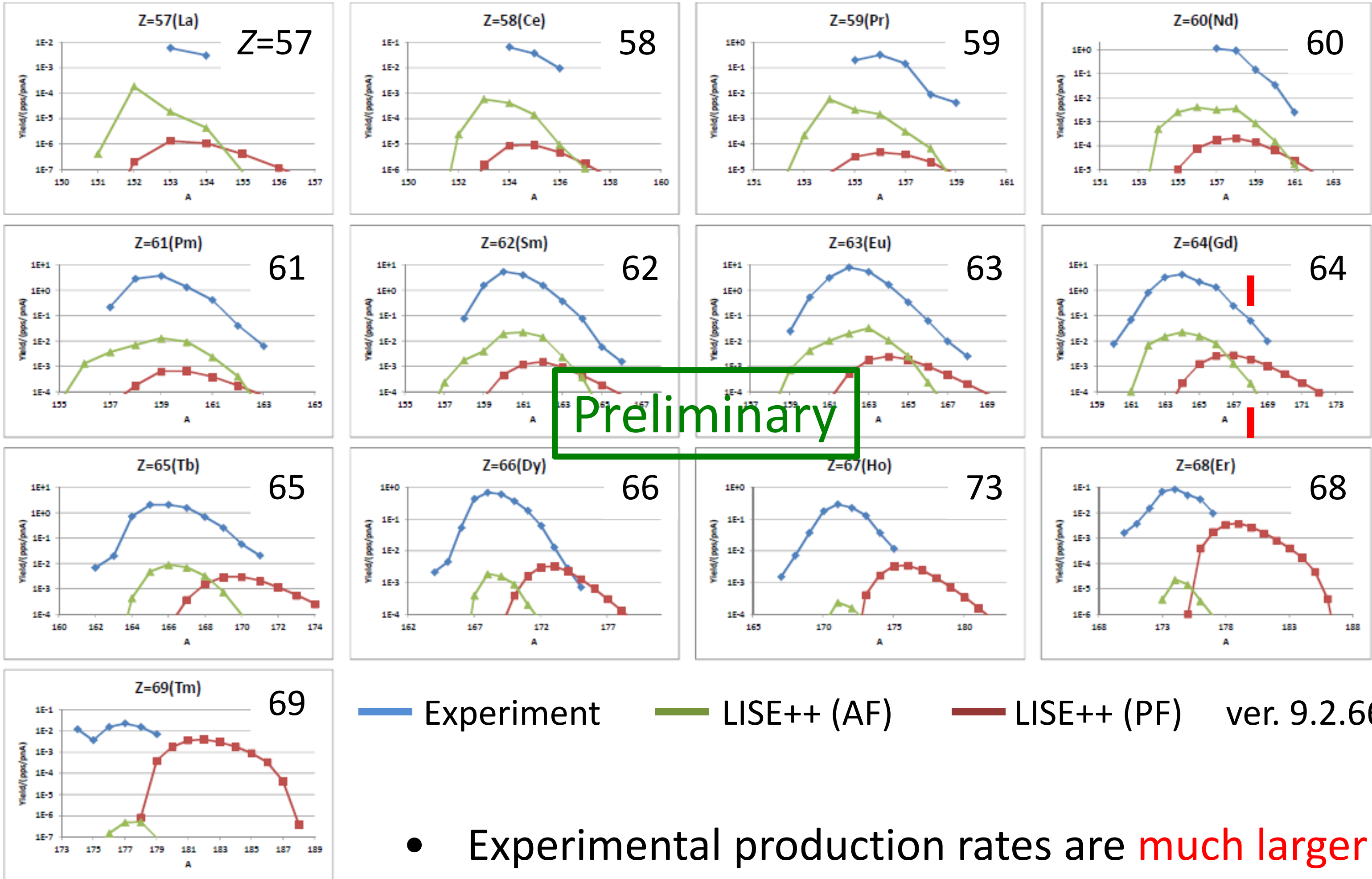


- Good agreement with LISE++ calculation with Abrasion fission model around the region of Z = 20 - 50.

Production rates of the fragments in setting-G4t-Be

$^{238}U^{86+}$ 345MeV/u + Be   Abrasion fission + Projectile fragmentation

(Center particle: $^{168}Gd^{63+\rightarrow 64+}$($Z$=64))



Experiment   LISE++ (AF)   LISE++ (PF)   ver. 9.2.66 β (=8.4.1)

*1 Distribution mode was used.

*2 The ΔE detectors were located at F12. The transmission between F7 to F12 was not considered (~50%).

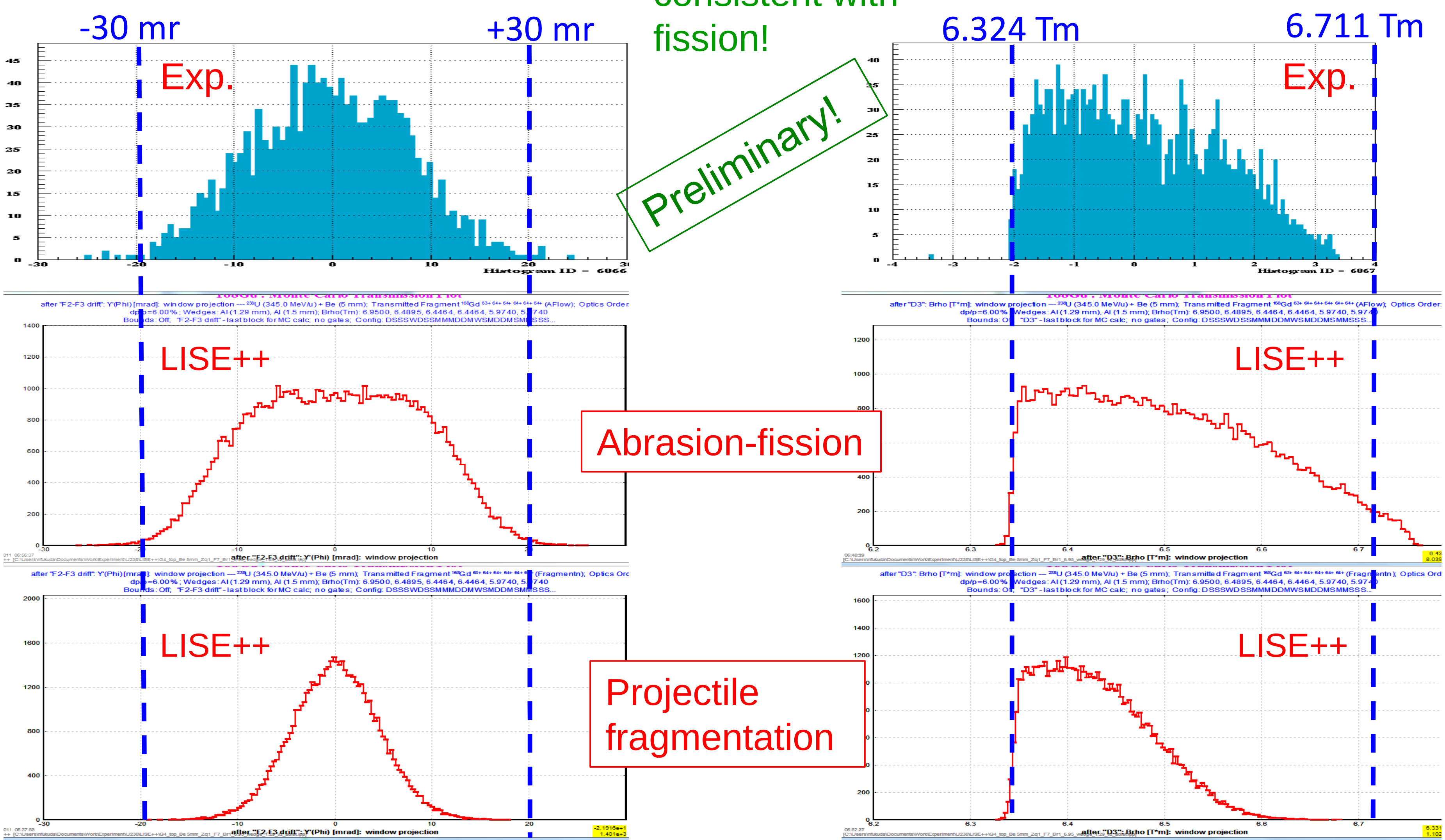
- Experimental production rates are much larger than the LISE++ calculation with AF model in the region of Z > 55.

Kinematics of fragments: angular and momentum distributions for ^{168}Gd (Z=64)

Y-angle(ϕ) at F3

Wide spreads: consistent with fission!

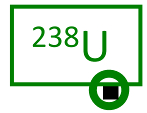
$B\rho$ distribution

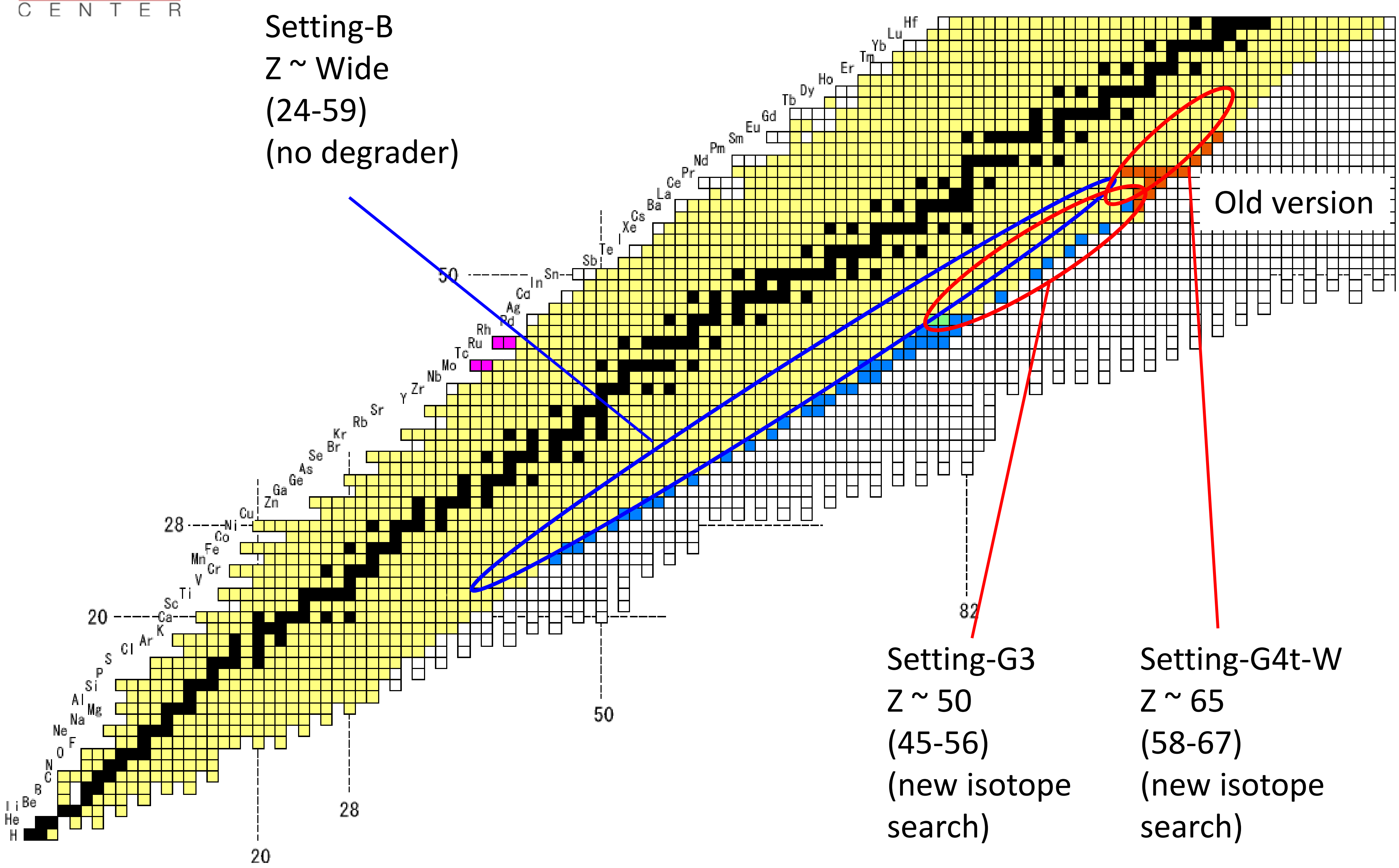


Pb / W target case
Coulomb Fission + AF

Setting	B	G3	G4t-W
Region	Z ~ wide (24 - 59)	Z ~ 50 (45 - 56)	Z ~ 65 (58 - 67)
Production mechanism	Coulomb fission + Abrasion fission		
Target	Pb 1.5 mm	Pb 0.95 mm + Al 0.3 mm	W 0.7 mm
$B\rho$ (Tm)	6.992	7.706	6.950
$\Delta p/p$	±0.1%	±3%	-2%/+3%
Degrader	No	F1: 2.56 mm F5: 1.8 mm	F1: 1.27 mm F5: 1.40 mm
F2 slit (mm)	±50	±15 mm	-4/+15
F7 slit (mm)			±15

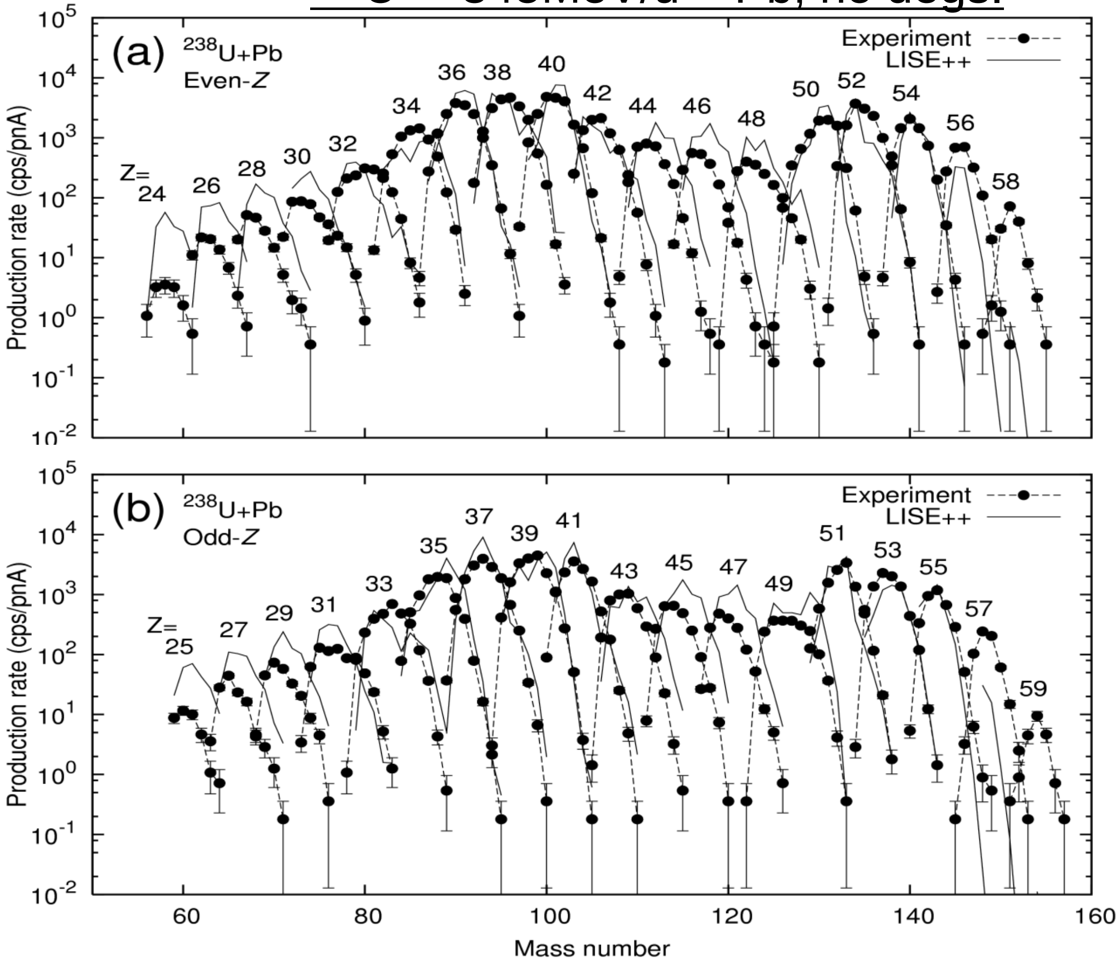
Region of the settings (heavy-*Z* target)





Production rates of the fragments in setting-B and comparison with LISE++ predictions by AF + CF model

$^{238}U^{86+}$ 345MeV/u + Pb, no degs.

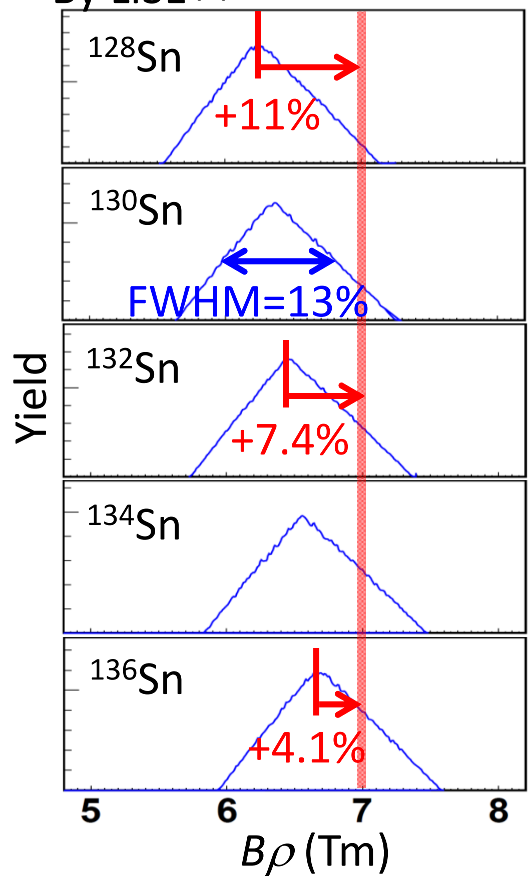


Coulomb Fission + AF

—— : LISE++ Ver. 8.4.1

$B\rho$ = 7.0 Tm ± 0.1%

By LISE++

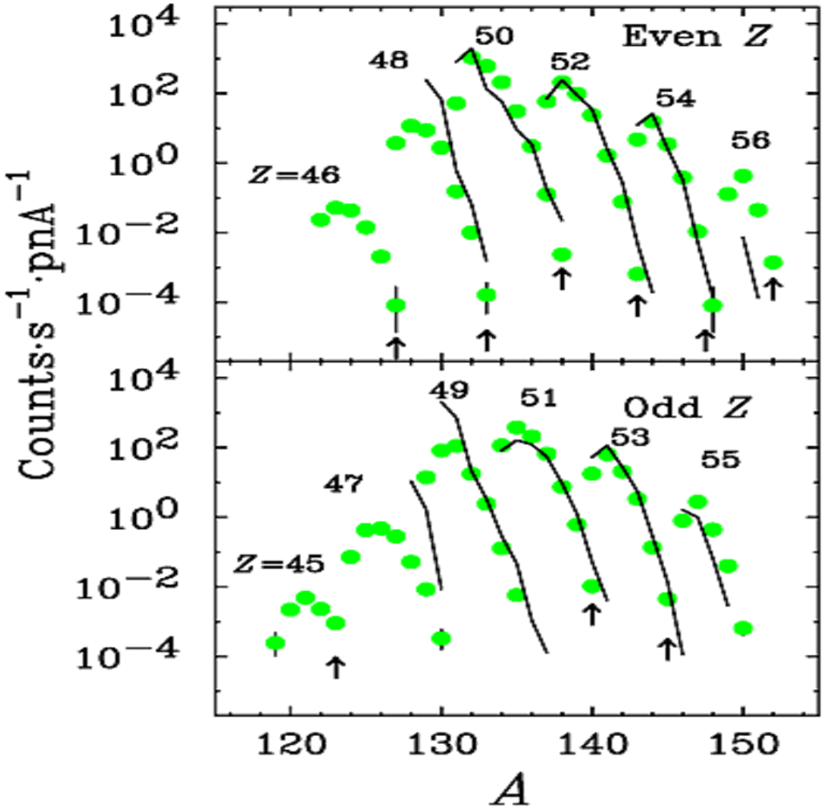


- Fairly good agreement with LISE++ calculation with "Coulomb fission + Abrasion fission".
  - Good agreement at the two peak regions (Z ~ 38 and Z ~ 52).
  - Discrepancy is seen at other regions.

Production rates of setting-G3 fragments and comparison with LISE++ predictions by CF+AF model

$^{238}U^{86+}$ 345MeV/u + Pb   *Z* ~ 50   Coulomb fission + AF

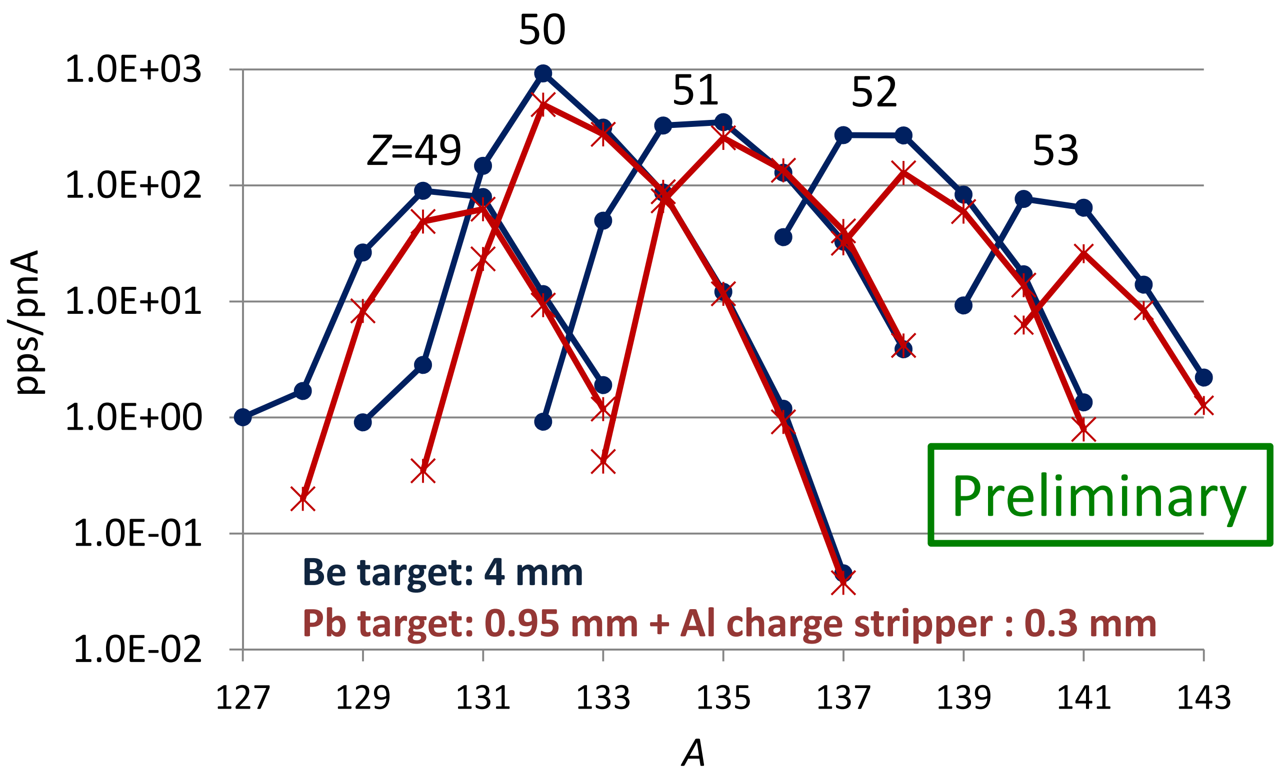
● SettingG3: Z~50   —— LISE++(ver. 8.4.1)



- Good agreement with LISE++ calculation with "Coulomb fission + Abrasion fission" models around the region of *Z* ~ 50 (higher-*Z* peak).

Production rate comparison between G3'-Be and G3'-Pb

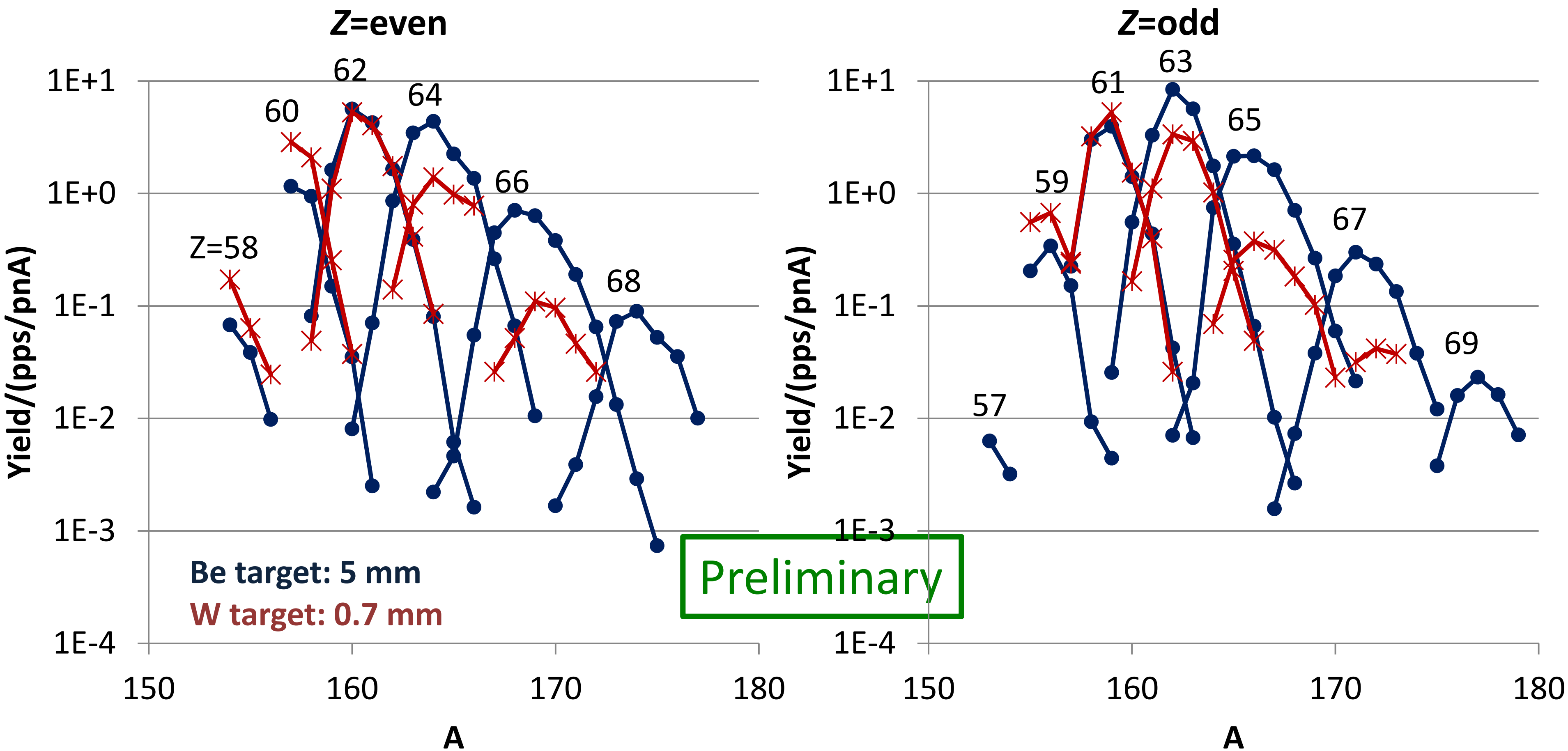
These Be and Pb targets are energy-loss equivalent thick.
The BigRIPS settings are the same.



- In the neutron-rich region, the production rates are almost the same in these setting.

Production rate comparison between G4t-Be and G4t-W

These Be and W targets are energy-loss equivalent thick.
The BigRIPS settings are the same.



- In $Z > 62$ region, the production rates of the neutron-rich nuclei with Be target are larger than the ones with W target.

Summary for the cross sections of RIs produced by in-flight fission of ^{238}U

- Neutron-rich isotopes were produced by the in-flight fission of ^{238}U beam at 345 MeV/u and compared with the LISE++ calculation.
- Two reaction mechanism.
  - Be target: Abrasion fission
  - Pb / W target: Coulomb fission + Abrasion fission
- In Be target case (Abrasion fission).
  - At $20 < Z < 50$ region, the LISE++ calculation estimates the production rates well.
  - At $50 < Z$ region, the LISE++ calculation underestimates the production rates.

  → We speculate that this is because the parameters of the LISE++ AF model were obtained from the cross section data in the region of Z = 20-46 (GSI experiment). The parameterization is needed to be improved incorporating data in the region of higher Z.
- In Pb / W target case (Coulomb fission + Abrasion fission).
  - At the two peak regions ($32 < Z < 43$ and $49 < Z < 55$), good agreement was obtained.
  - We observed the discrepancy in the regions of $24 < Z < 32$, 43 <~ Z <~ 49, 56 <~ Z <~ 67. These origins are under investigation.
- The production rates of the isotopes produced with Be target and heavy-Z (Pb / W) targets whose thicknesses are energy-loss equivalent were compared.
  - At $Z \sim 50$, the production rates of the very neutron-rich isotopes produced with Be and Pb targets are almost the same.
  - $Z > 62$, the production rates of RIs produced with Be target is larger than the one with W target.